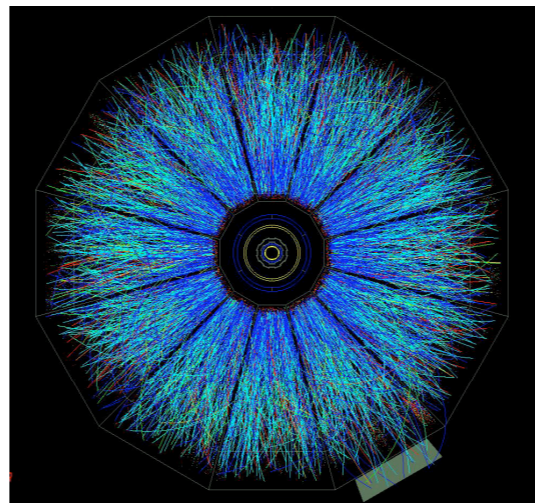


Rheometry of the Quark Gluon Plasma

Claude A. Pruneau for the STAR Collaboration

WAYNE STATE
UNIVERSITY

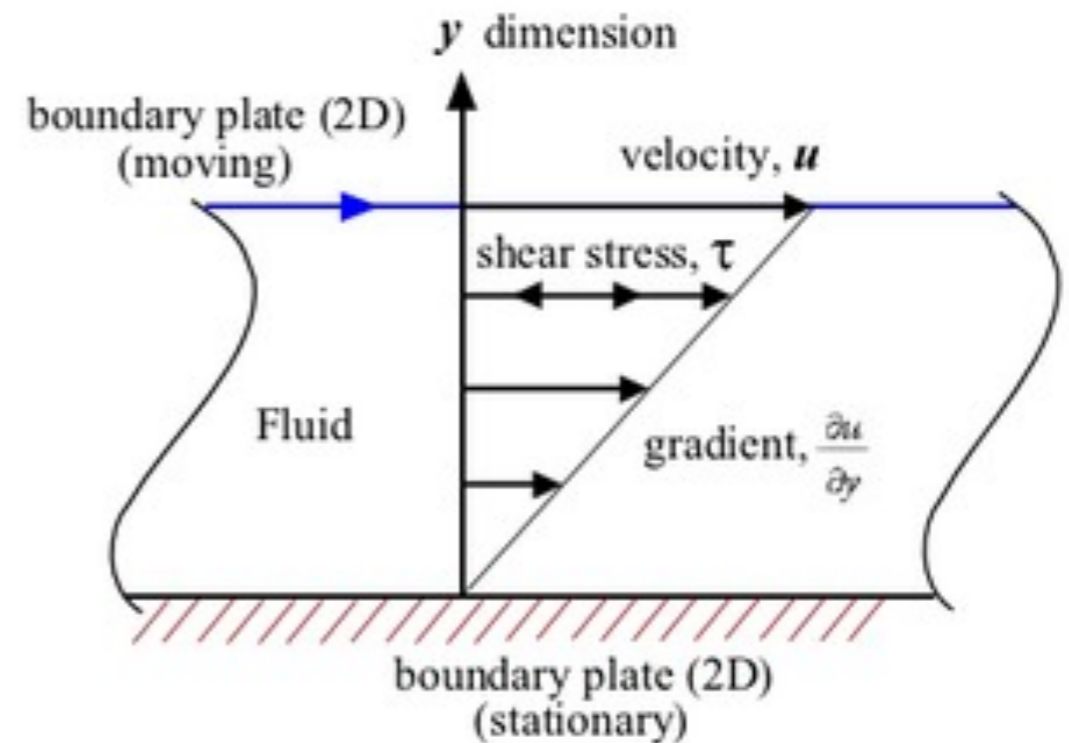
RHIC-AGS User Meeting
June 1, 2009



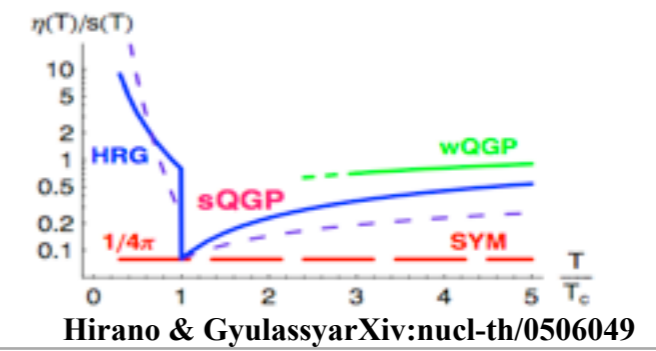
Viscosity

- Stress vs Deformation $\tau = \eta \frac{du}{dy}$
 - Velocity Gradient (m/s): du/dy
 - Shear Stress (Pa): τ
 - Dynamic viscosity (Pa s): η
- Kinematic Viscosity (m²/s): $\nu = \frac{\eta}{\rho}$
 - Density (kg/m³): ρ
- Relation to the Mean Free Path (m): λ

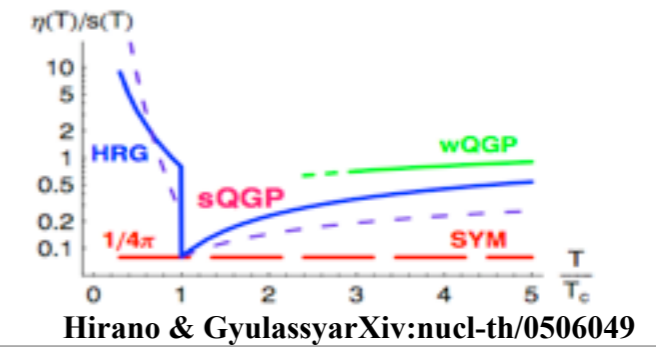
$$\nu = \frac{1}{2} \bar{u} \lambda$$



Reometry of the QGP: $\nu = \frac{\eta}{T_c s}$

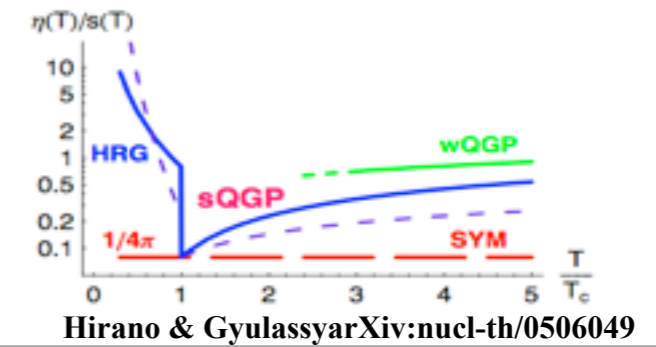


Reometry of the QGP: $\nu = \frac{\eta}{T_c s}$



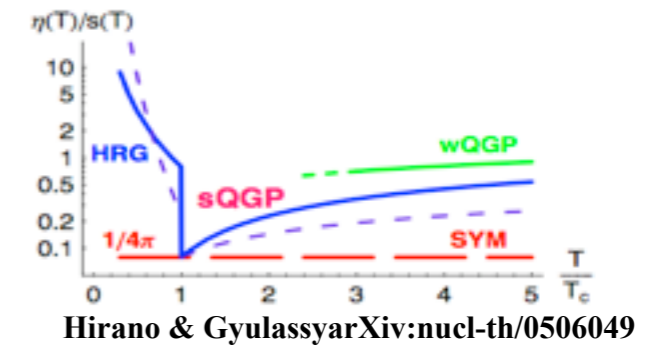
- Formation of (nearly) perfect fluid => Hydrodynamics works

Reometry of the QGP: $\nu = \frac{\eta}{T_c s}$

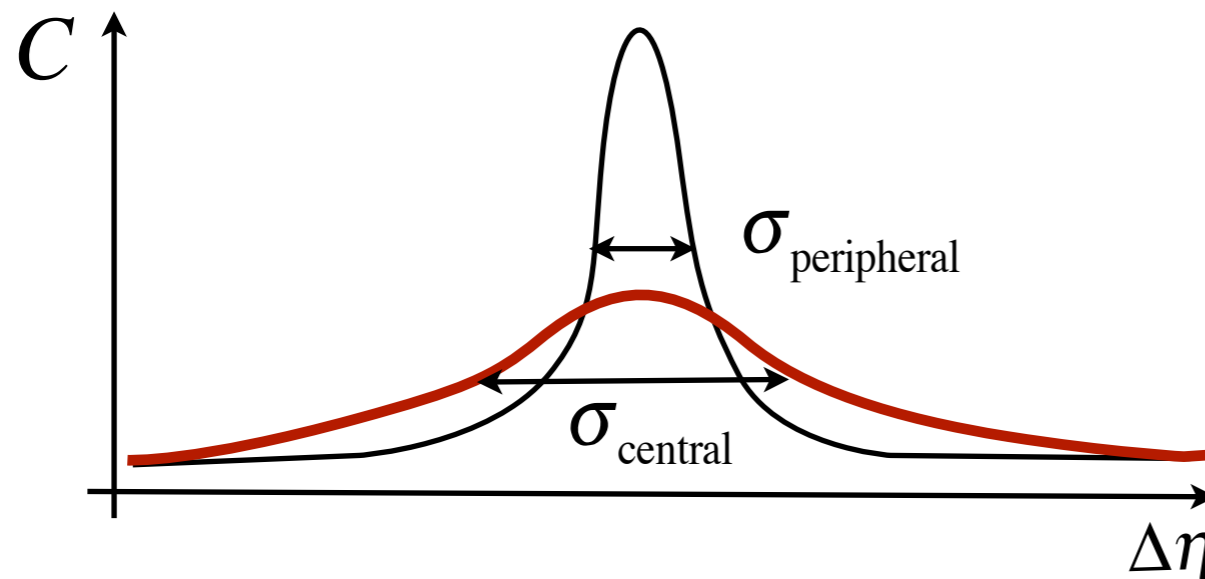


- Formation of (nearly) perfect fluid => Hydrodynamics works
- Flow Measurements

Reometry of the QGP: $v = \frac{\eta}{T_c s}$



- Formation of (nearly) perfect fluid => Hydrodynamics works
- Flow Measurements
- Transverse Momentum Correlations
 - Measurement based on broadening with collision centrality of pT correlation function vs. pseudorapidity --- S. Gavin, M. Abdel-Aziz, nucl-th/060606.

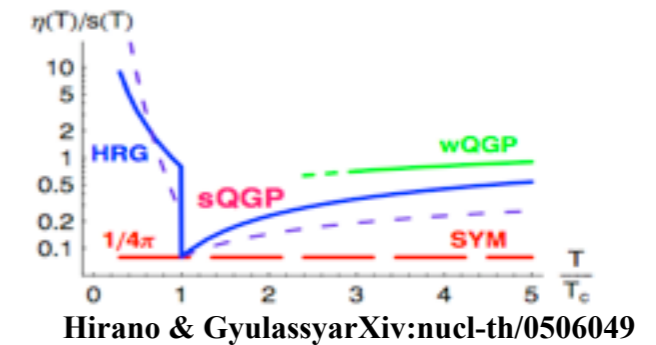


$$\sigma_c^2 - \sigma_p^2 = 4v \left(\tau_{f,p}^{-1} - \tau_{f,c}^{-1} \right)$$

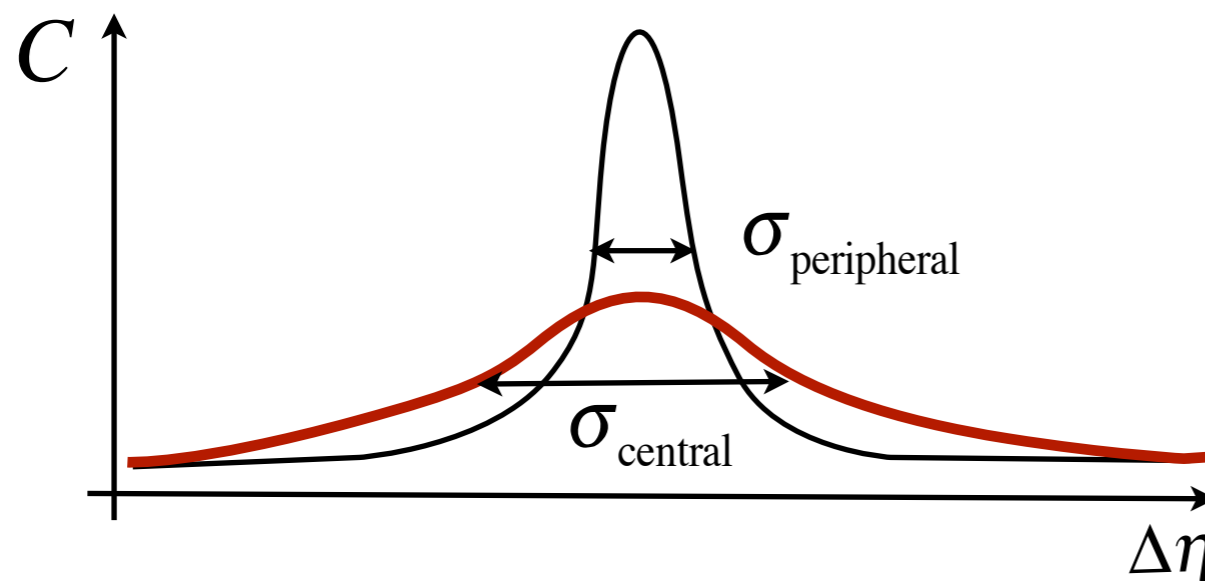
$\tau_{f,p}$
 $\tau_{f,c}$

Freeze out Times

Reometry of the QGP: $v = \frac{\eta}{T_c s}$



- Formation of (nearly) perfect fluid => Hydrodynamics works
- Flow Measurements
- Transverse Momentum Correlations
 - Measurement based on broadening with collision centrality of pT correlation function vs. pseudorapidity --- S. Gavin, M. Abdel-Aziz, nucl-th/060606.



$$\sigma_c^2 - \sigma_p^2 = 4v \left(\tau_{f,p}^{-1} - \tau_{f,c}^{-1} \right)$$

$\tau_{f,p}$
 $\tau_{f,c}$  Freeze out Times

• Observation of Conical Emission

- Significant energy loss of high pt partons inside A+A medium.
- (Possible) formation of in-medium shock waves and conical emission.
- Mach cone shocks dissipate exponentially w.r.t. wave-number and distance

$$\sim \exp(-k\Gamma x)$$

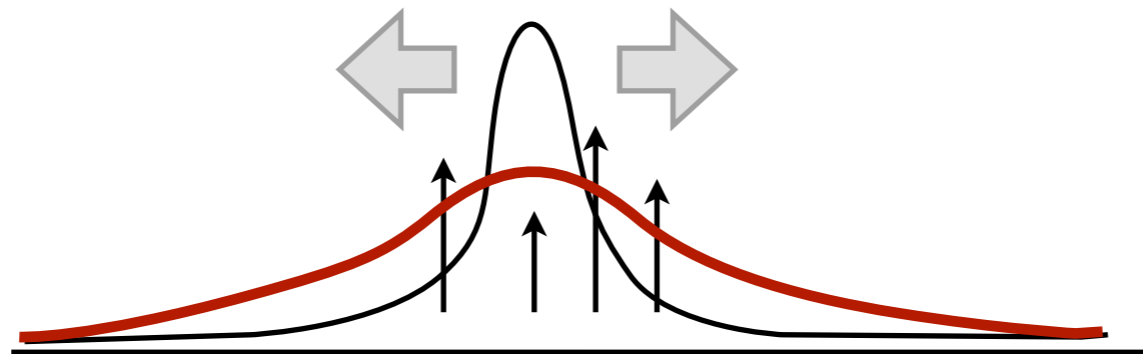
$$\Gamma = \frac{4}{3} \frac{\eta}{\varepsilon + p}$$

η = shear viscosity
 ε = energy density
 p = pressure

More about the model and this analysis

- See talk by S. Gavin
- Shear viscosity broadens the rapidity correlations of the momentum current
- Broadening determined transverse momentum correlation function vs rapidity
 - Width increases with life time of the system (i.e. more diffusion).
- But, other effects contribute to the longitudinal shape of the correlation function
 - Resonance decays,
 - Thermal broadening
 - Jets
 - etc.
- Contributions from the QGP, mixed, and hadronic phase.
- We **assume** the broadening is **dominated** by effects associated with **QGP shear viscosity**.

$$\sigma_c^2 = \sigma_{Diffusion}^2 + \sigma_{Thermal}^2 + \sigma_0^2$$



(Integral) Transverse Momentum Correlations

Gavin et al.

$$0.08 < \eta/s < 0.3$$

based on

p_T correlations

STAR, J. Phys. G32, L37, 2006 (AuAu 200 GeV)

$$\eta/s \approx 0.08$$

Number density correlations

STAR, PRC 73, 064907, 2006 (AuAu 130 GeV)

$$\eta/s \approx 0.3$$

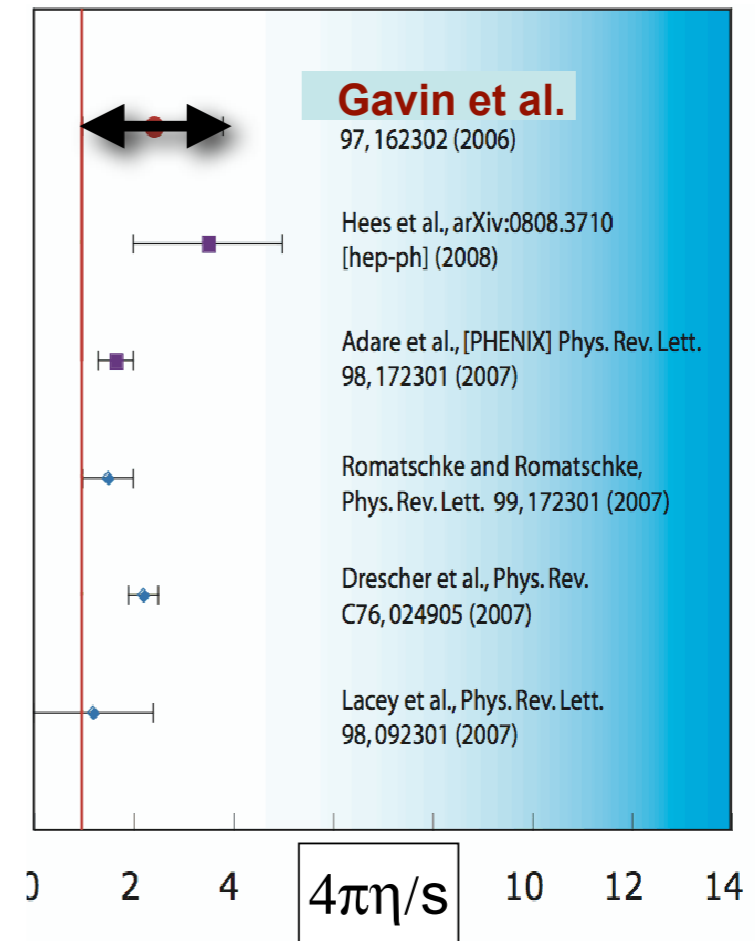
But, ...

Proper estimation of η/s requires an observable with contributions from number density & pT correlations

$$C = \langle p_{t1} p_{t2} \rangle - \langle p_t \rangle^2$$

$$\langle p_{t1} p_{t2} \rangle \equiv \frac{1}{\langle N \rangle^2} \left\langle \sum_{\text{pairs } i \neq j} p_{ti} p_{tj} \right\rangle$$

$$\langle p_t \rangle \equiv \frac{1}{\langle N \rangle} \langle \sum p_{ti} \rangle$$



Differential Transverse Momentum Correlations

M. Sharma & C. A. Pruneau, Phys. Rev. C 79 (2009) 024905

- Introducing Differential Momentum Covariance

$$\tilde{C}(\Delta\eta, \Delta\varphi) = \frac{\left\langle \sum_{i=1}^{n_\alpha} \sum_{j \neq i=1}^{n_{\alpha'}} p_i(\eta_1, \varphi_1) p_j(\eta_2, \varphi_2) \right\rangle}{\langle n(\eta_1, \varphi_1) n(\eta_2, \varphi_2) \rangle} - \frac{\left\langle \sum_{i=1}^{n_\alpha} p_i(\eta_1, \varphi_1) \right\rangle \left\langle \sum_{j=1}^{n_{\alpha'}} p_{\alpha,j}(\eta_2, \varphi_2) \right\rangle}{\langle n(\eta_1, \varphi_1) \rangle \langle n(\eta_2, \varphi_2) \rangle}$$

$$\Delta\eta = \eta_1 - \eta_2$$

$$\Delta\varphi = \varphi_1 - \varphi_2$$

$$p_i(\eta, \varphi) \quad \text{Transverse Momentum}$$

$$n(\eta, \varphi) \quad \text{Number of particles at } p_i(\eta, \varphi)$$

- To be distinguished from

$$\rho_2^{\Delta p_1 \Delta p_2}(\Delta\eta, \Delta\varphi) = \frac{\left\langle \sum_{i=1}^{n_\alpha} \sum_{j \neq i=1}^{n_{\alpha'}} (p_i(\eta_1, \varphi_1) - \langle p(\eta_1, \varphi_1) \rangle) (p_j(\eta_2, \varphi_2) - \langle p(\eta_2, \varphi_2) \rangle) \right\rangle}{\langle n(\eta_1, \varphi_1) n(\eta_2, \varphi_2) \rangle}$$

Integral version measured by STAR, PRC 72 (2005) 044902

- Two observables are similar, but quantitatively different (see next slide)
- Study both:
 - $\tilde{C}(\Delta\eta, \Delta\varphi)$ is what we need.
 - $\rho_2^{\Delta p_1 \Delta p_2}(\Delta\eta, \Delta\varphi)$ is essentially same as $\Delta\sigma_{p_t}^2(\Delta\eta\Delta\varphi)$ reported by STAR (J. Phys. G32, L37, 2006).
 - More info than integral correlations

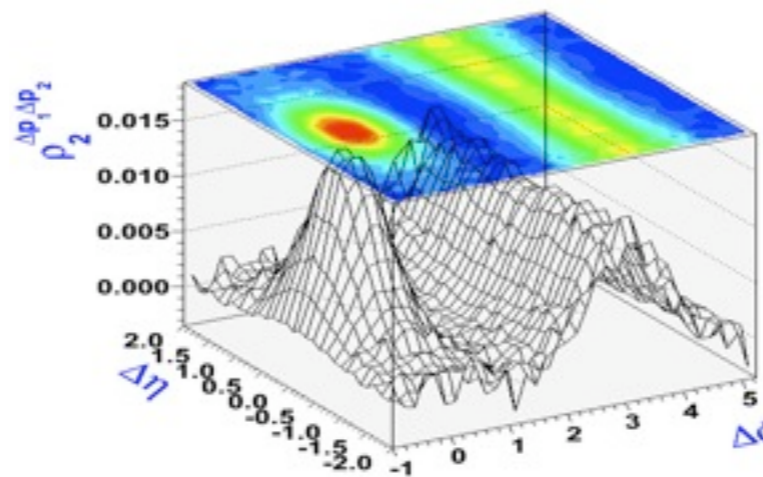
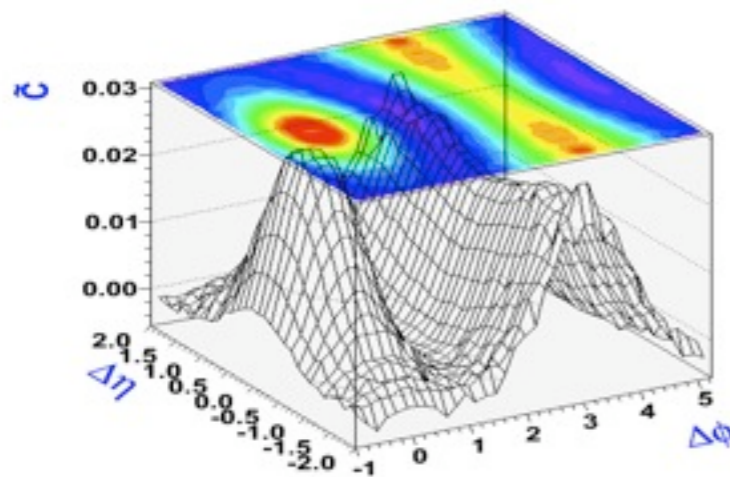
Comparative Study of $\rho_2^{\Delta p_1 \Delta p_2}$ and \tilde{C}

- Based on PYTHIA p+p collisions at $\sqrt{s} = 200 \text{ GeV}$

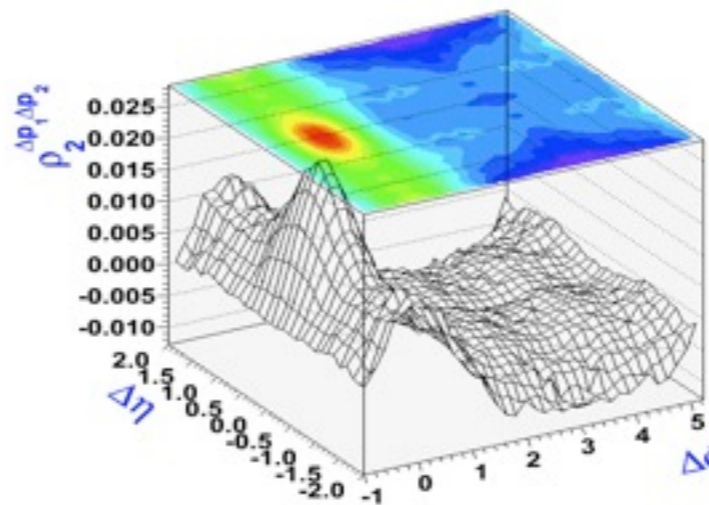
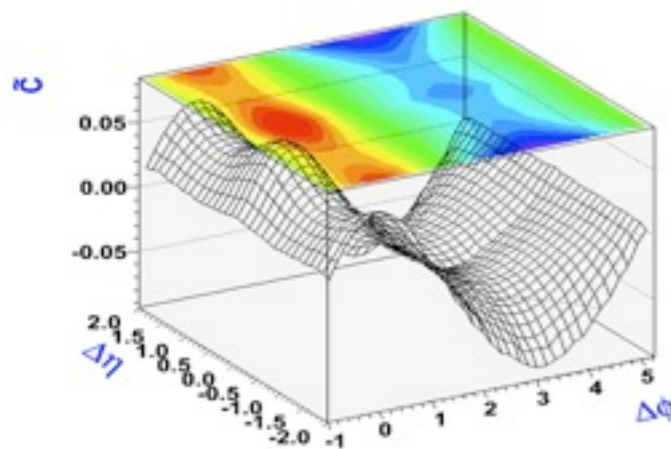
$$0.2 < p_T < 2.0 \text{ GeV}/c$$

$$|\eta| < 1$$

Similar distributions but different magnitudes



- PYTHIA Simulation including radial flow (transverse boost) with $v/c=0.3$



Near-side kinematic focusing, formation of ridge-like structure, Different shapes

S. A. Voloshin, arXiv:nucl-th/0312065
C. Pruneau, et al., Nuclear. Phys. A802, 107 (2008)

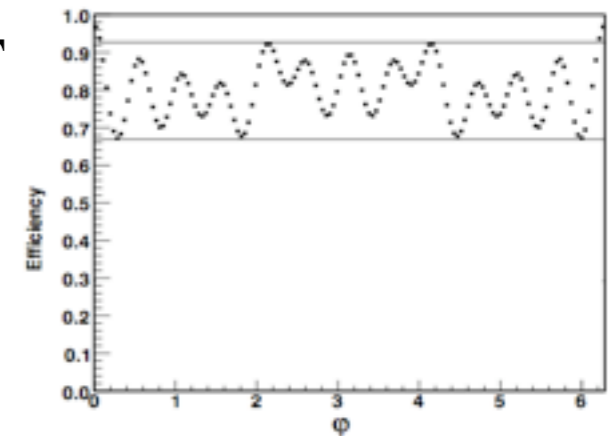
See M. Sharma & C. A. Pruneau, Phys. Rev. C 79 (2009) 024905 for more details.

Observable Robustness

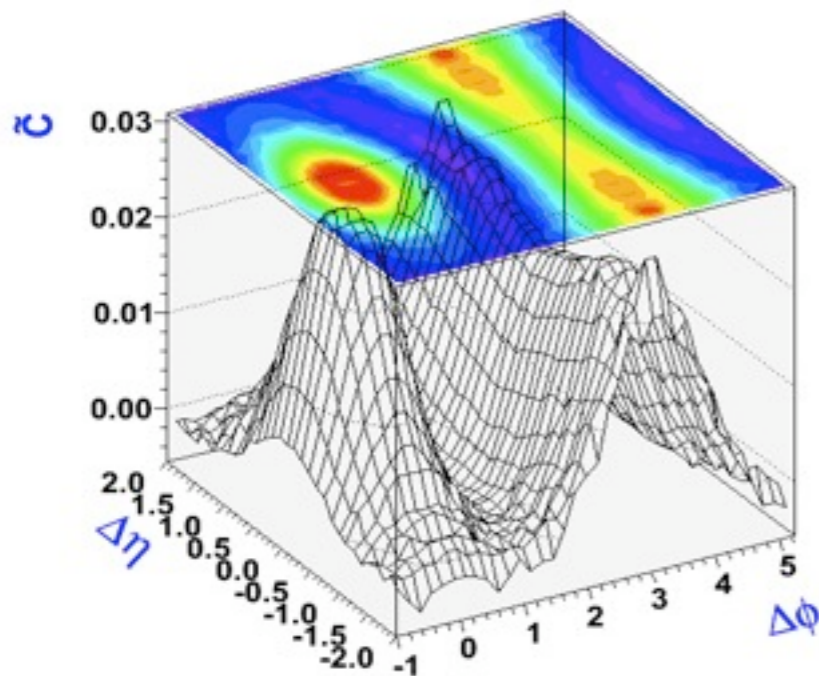
Study with PYTHIA, p+p collisions at $\sqrt{s} = 200$ GeV

Twelve fold angular efficiency dependence, and linear dependence on pT

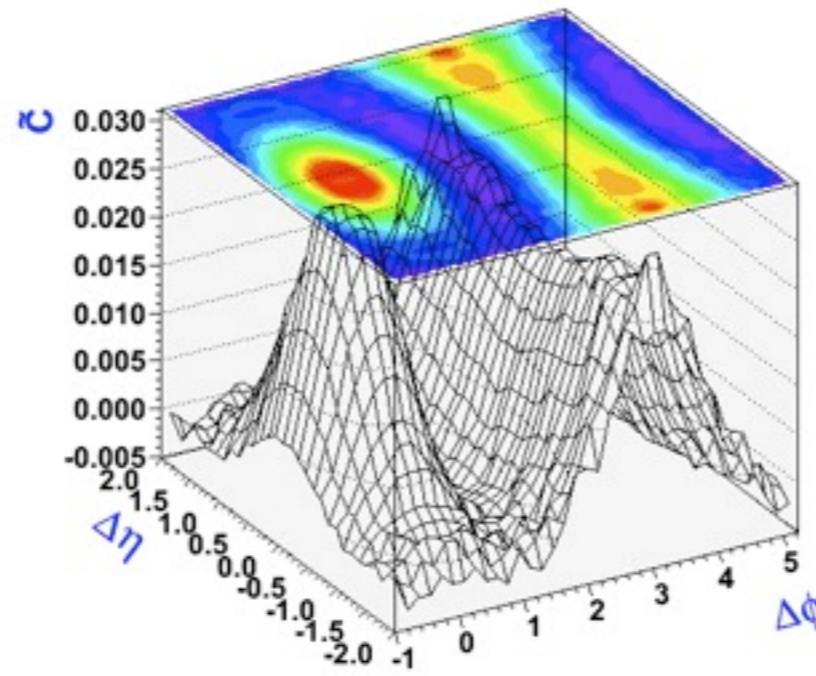
$$\varepsilon(\varphi, p_{\perp}) = \varepsilon_0 (1 - ap_{\perp}) \left[1 + \sum_{n=1}^{12} \varepsilon_i \cos(n\varphi) \right] \quad \varepsilon_0 = 0.8, a = 0.05$$



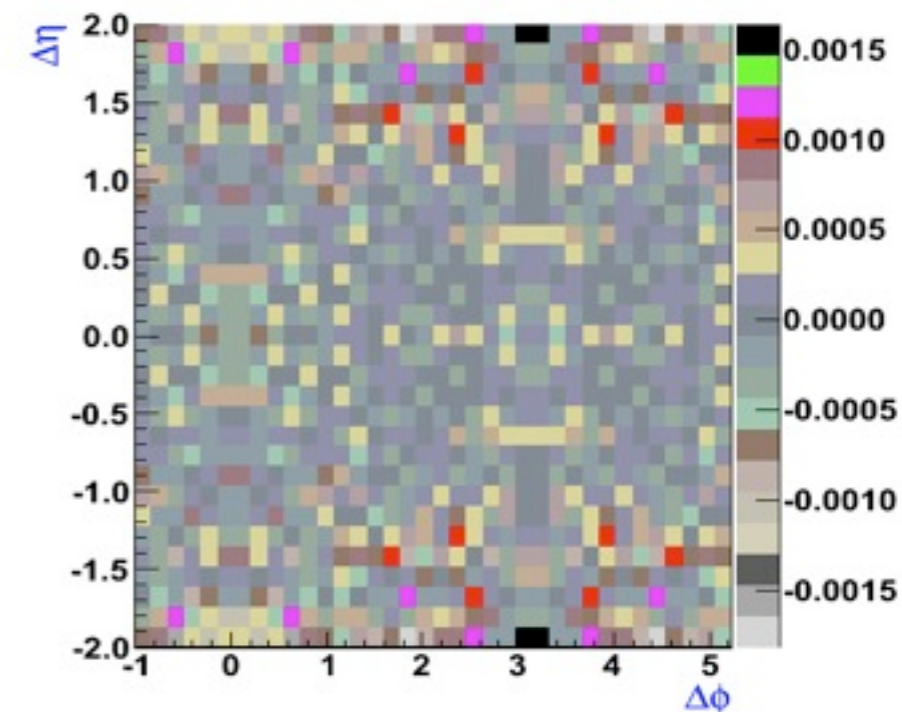
Efficiency = 100%



Efficiency = 80%



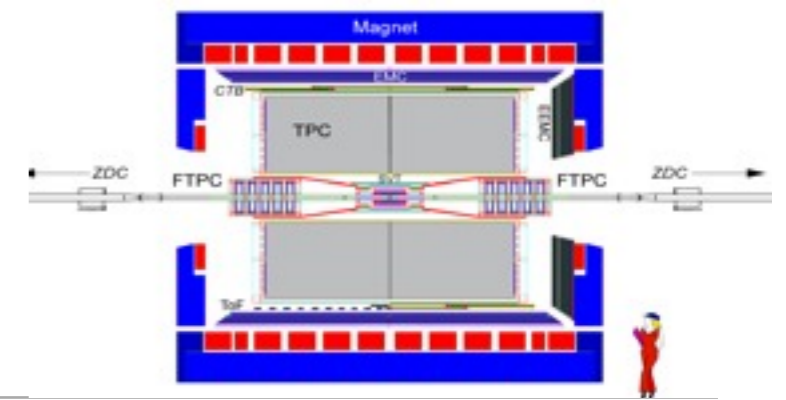
Difference



Statistical error = 0.001, difference = 0.0005 => Robust Observable

Further studies in progress

STAR Analysis

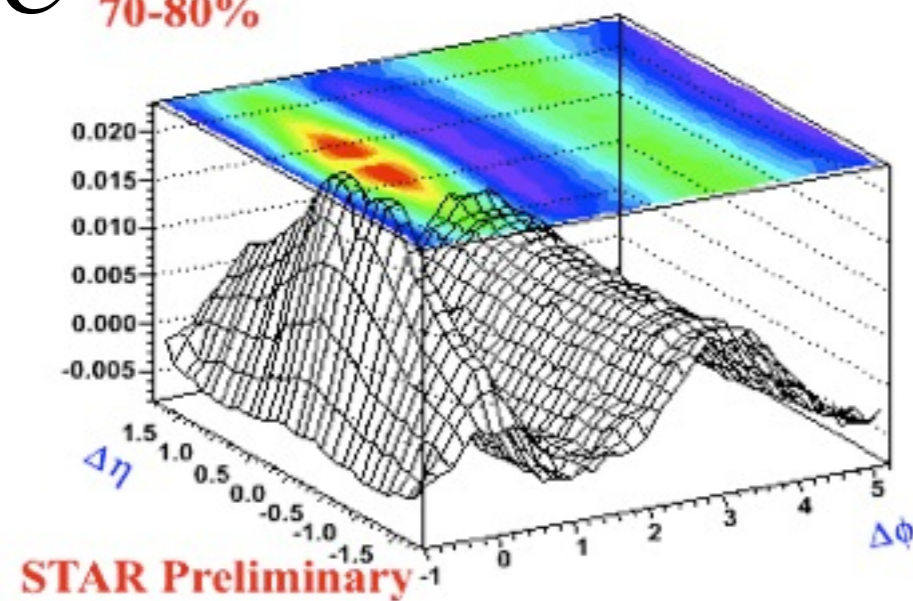


- Analyzed data from TPC, 2π coverage
- Dataset: Run IV AuAu 200 GeV
- Events analyzed: 10 Million
- Minimum bias trigger
- Track Kinematic Cuts applied:
 - $|\eta| < 1.0$
 - $0.2 < p_T < 2.0$ GeV/c
- Analysis done vs. collision centrality
 - Centrality slices: 0-5%, 5-10%, 10-20%.....

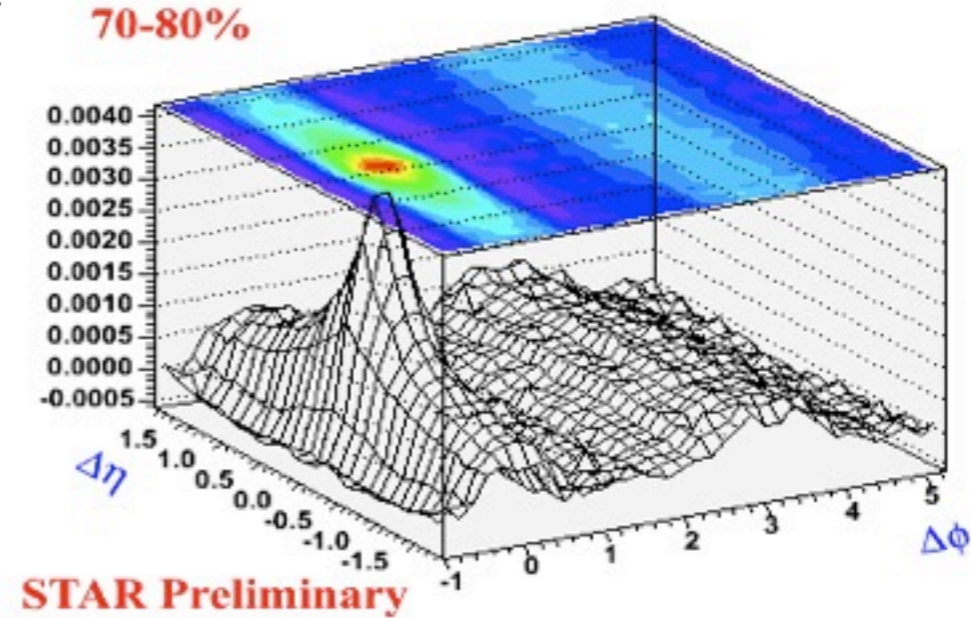
Results

Peripheral

\tilde{C} 70-80%

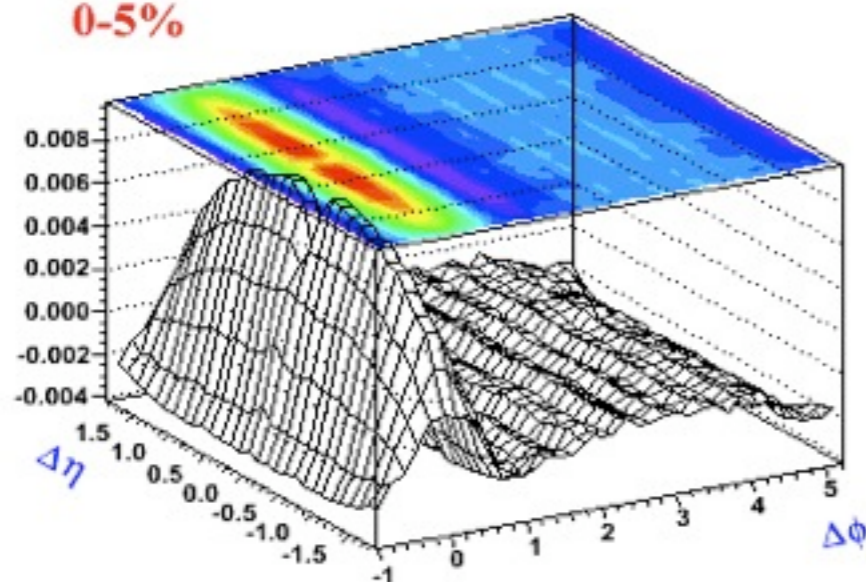


$\rho_2^{\Delta p_1 \Delta p_2}$ 70-80%

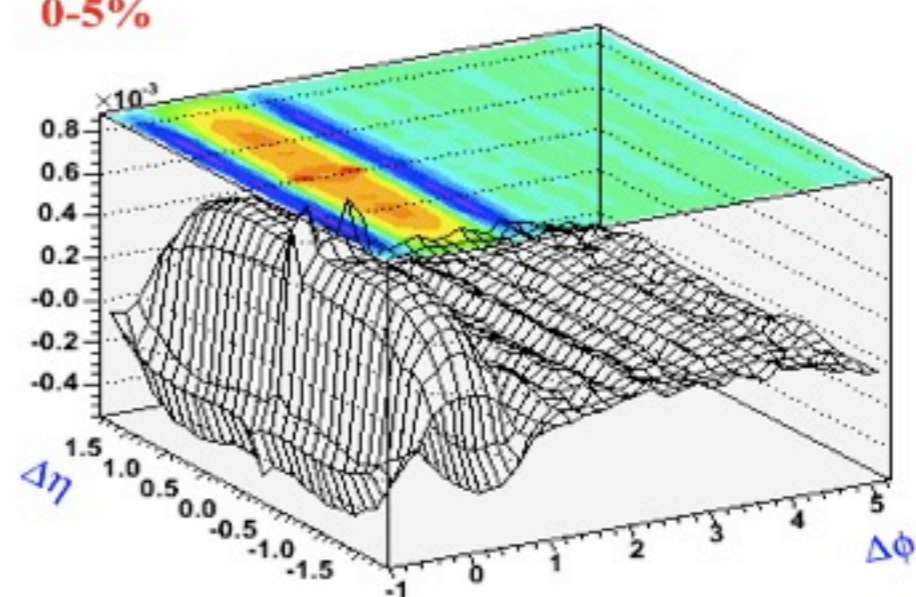


Central

0-5%



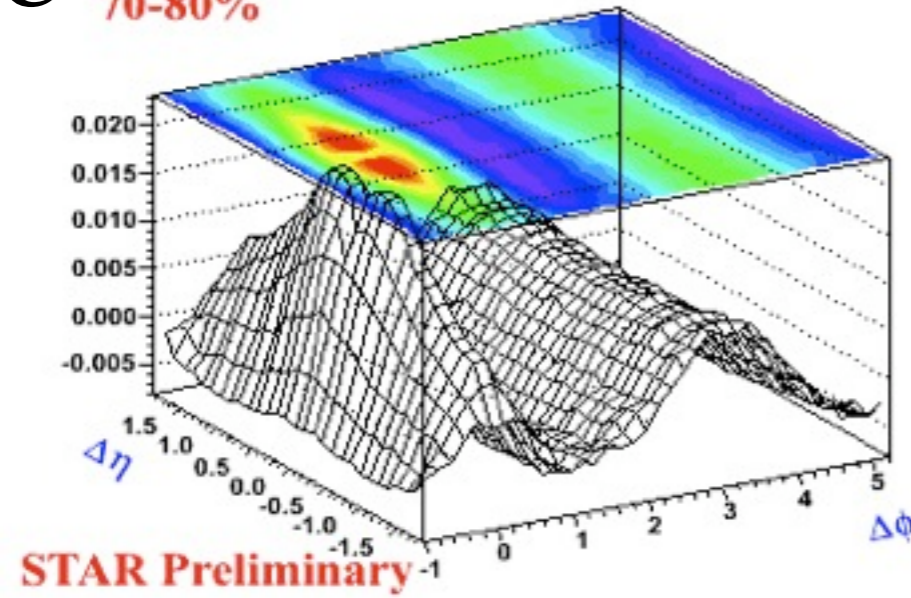
0-5%



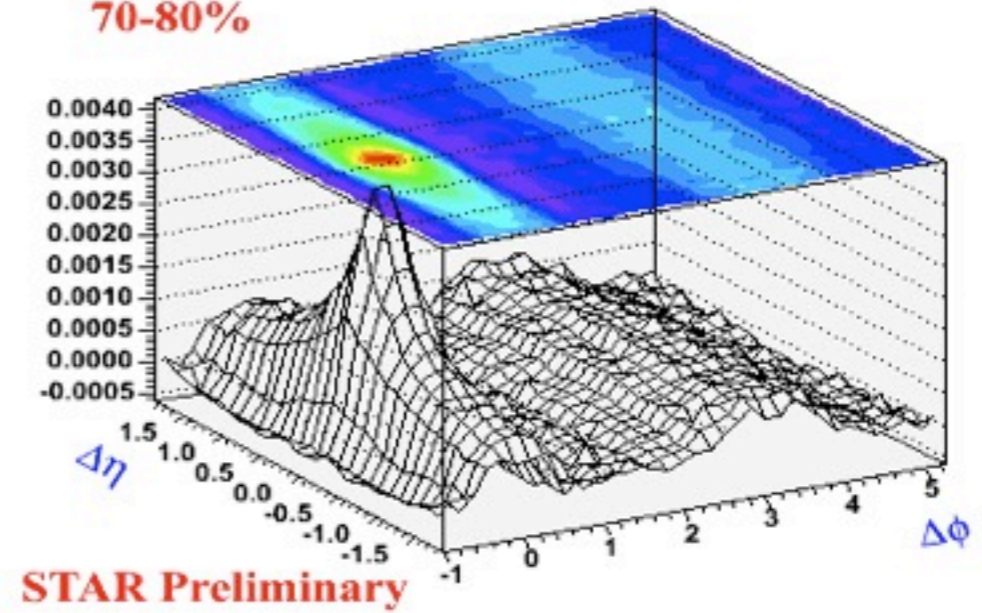
Results

Peripheral

\tilde{C} 70-80%

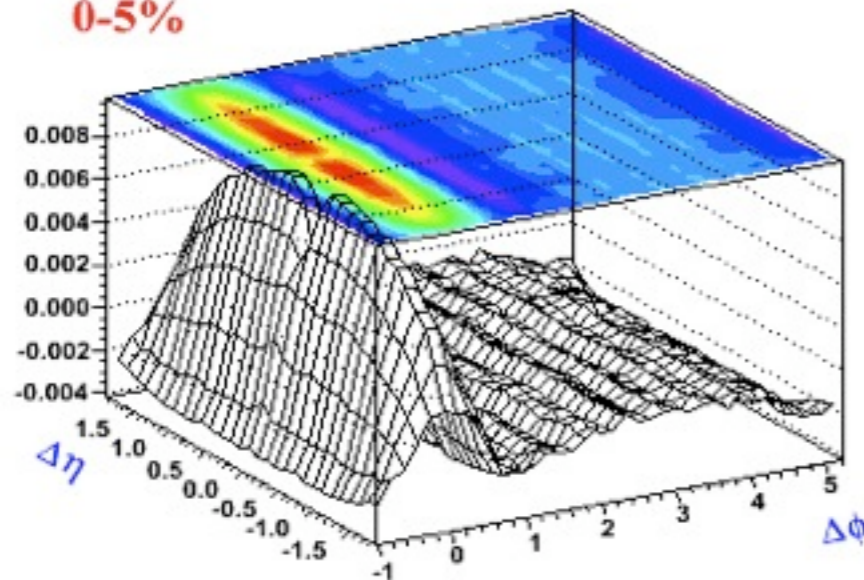


$\rho_2^{\Delta p_1 \Delta p_2}$ 70-80%

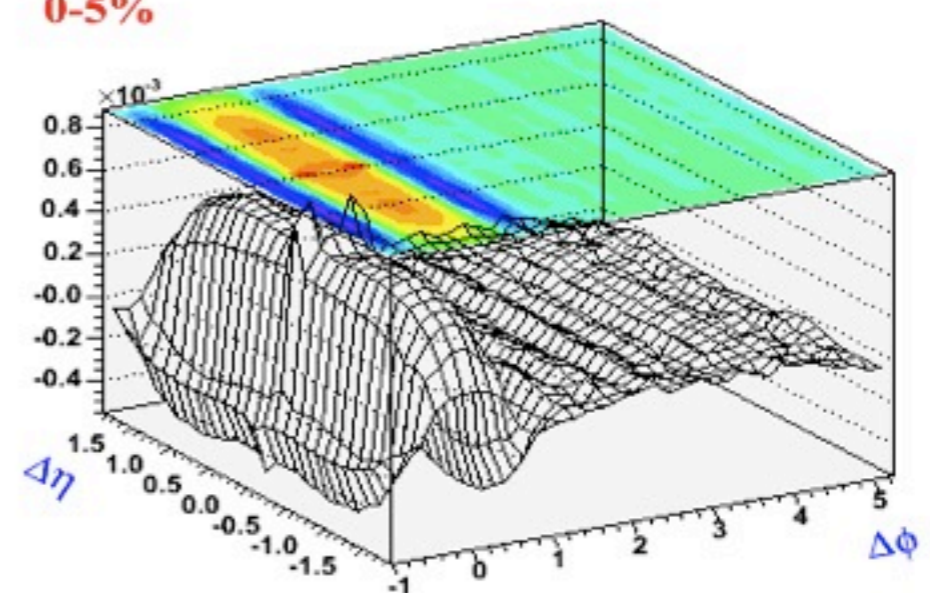


Central

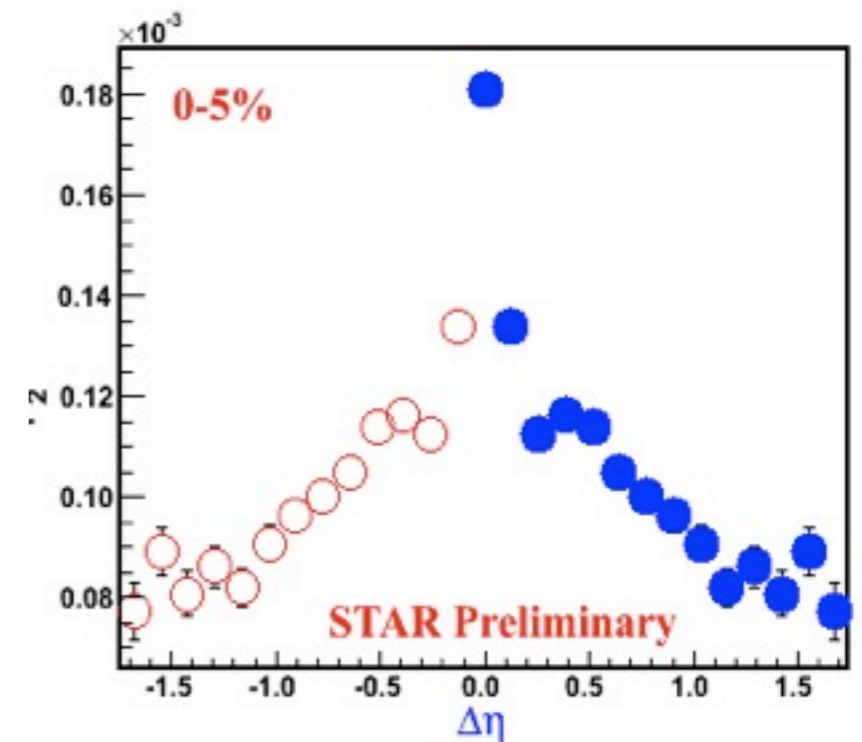
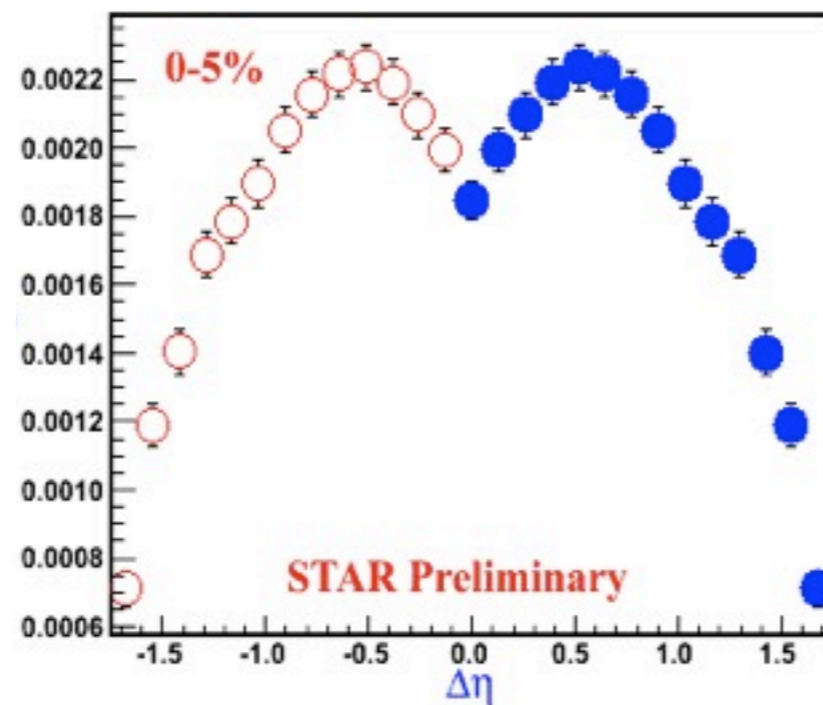
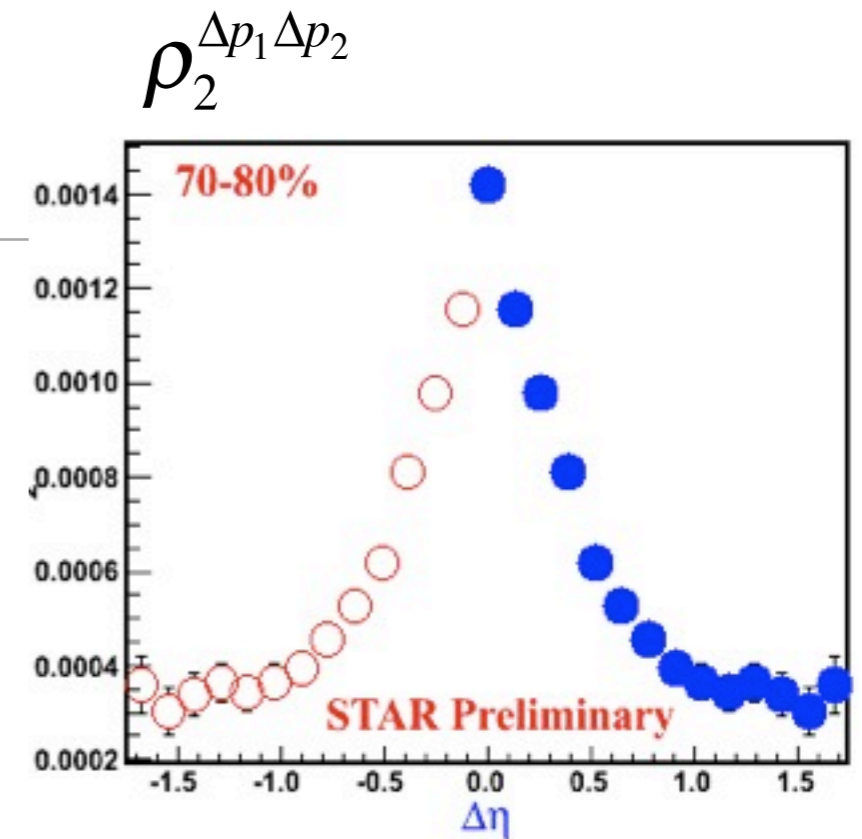
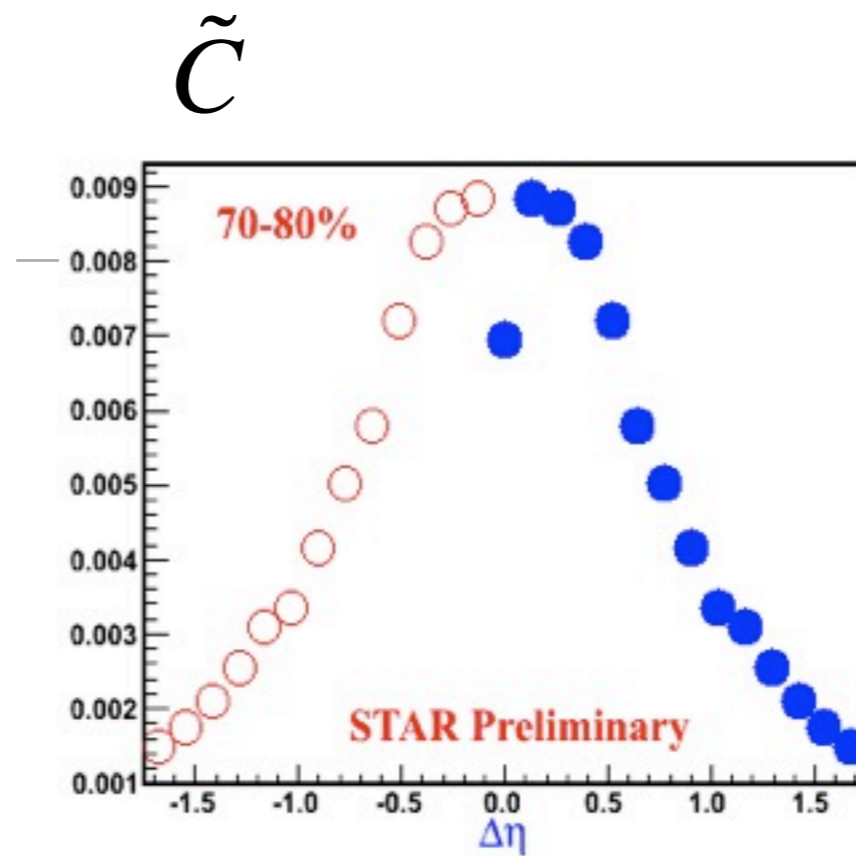
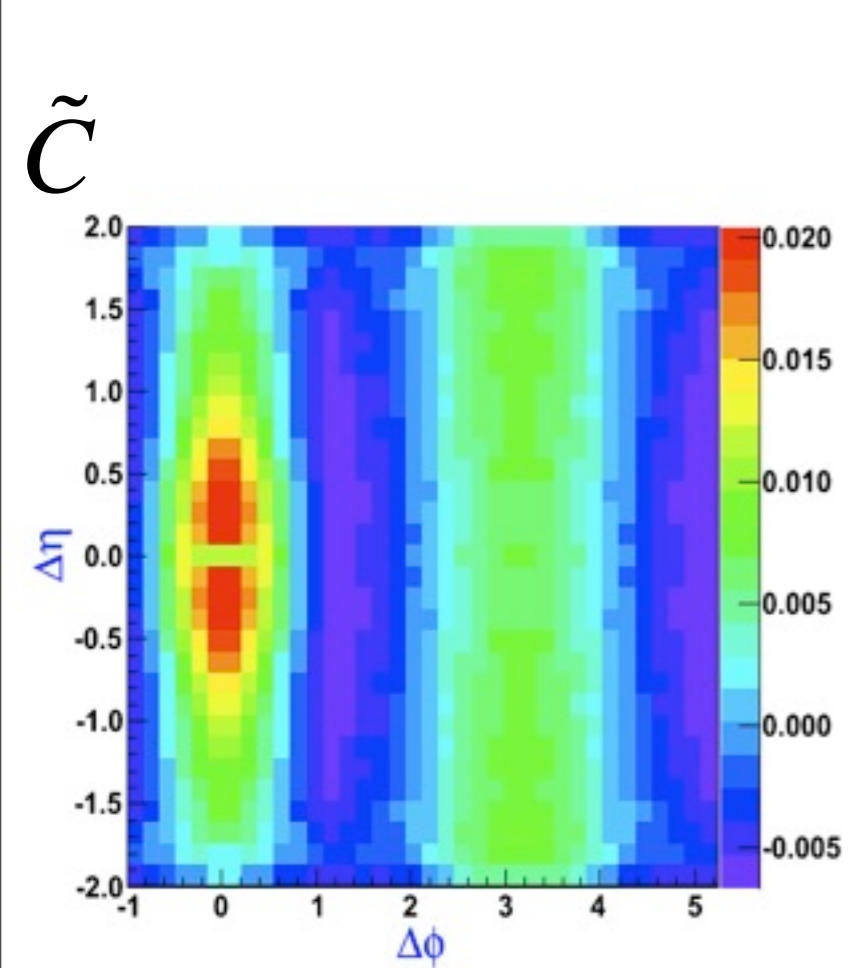
0-5%

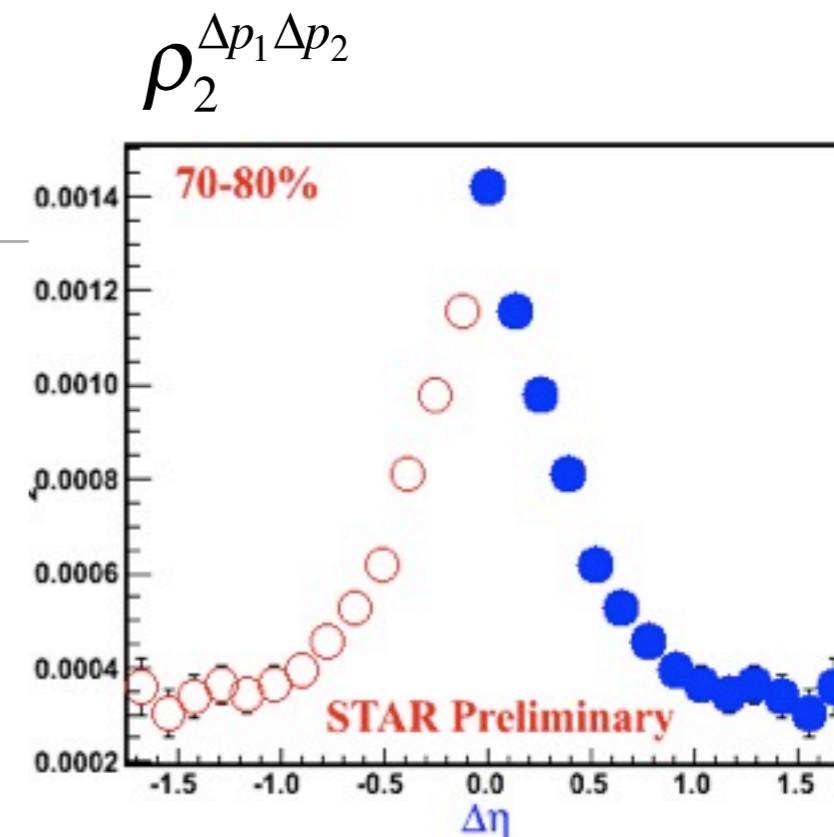
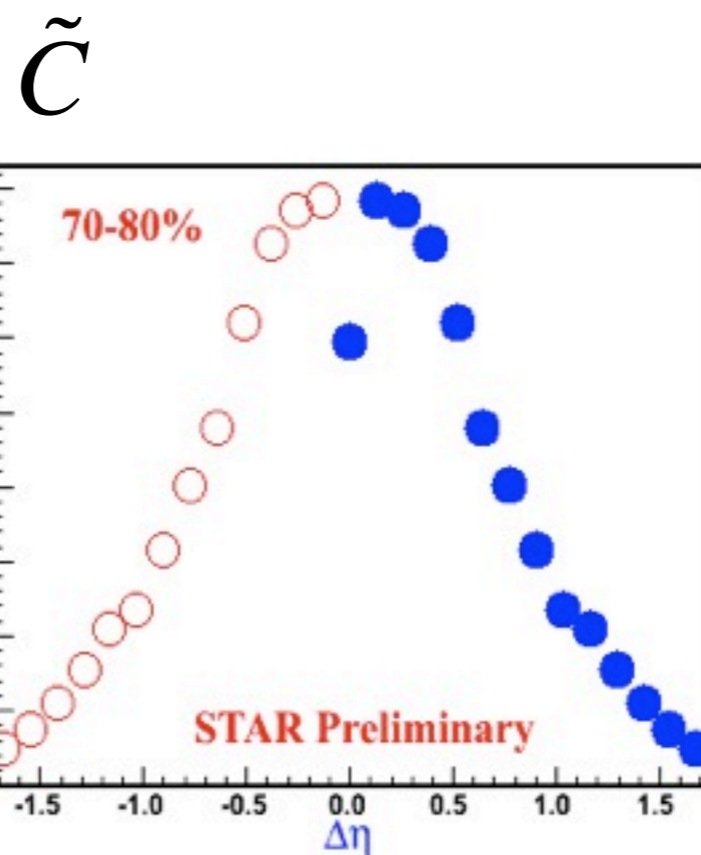
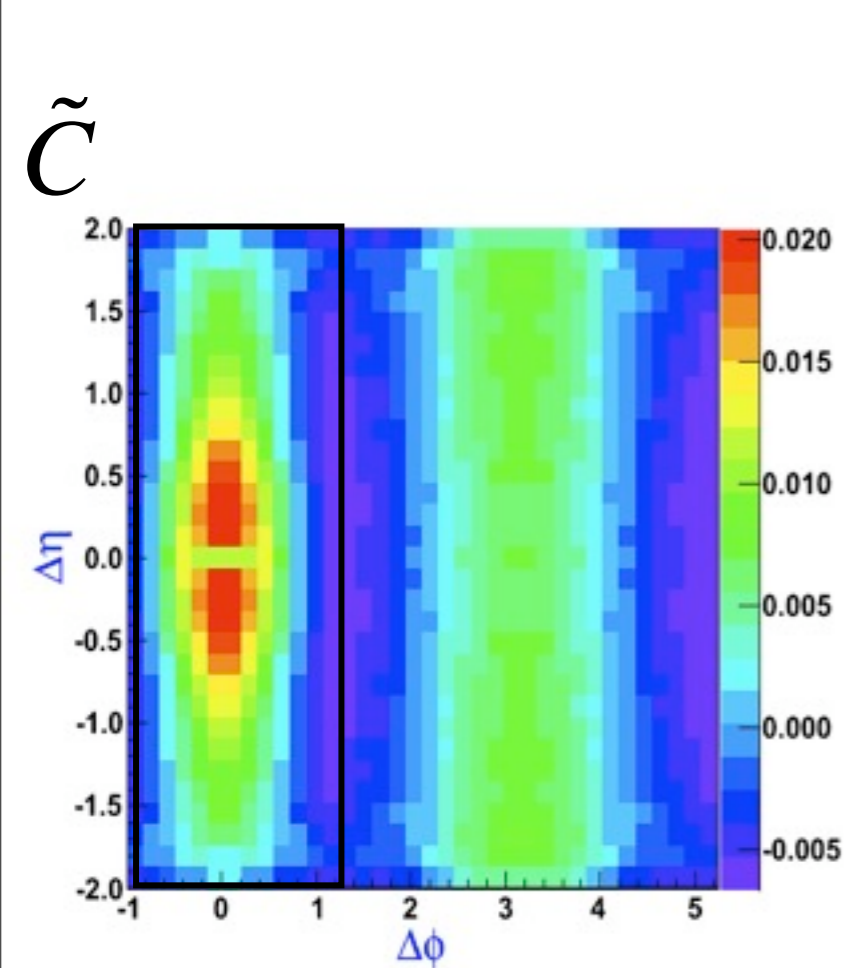


0-5%

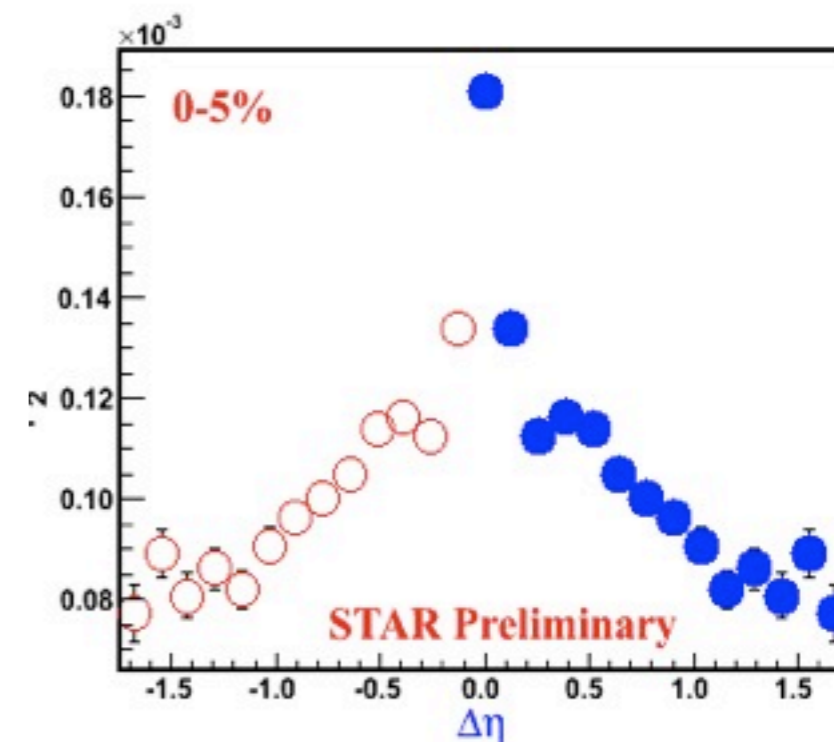
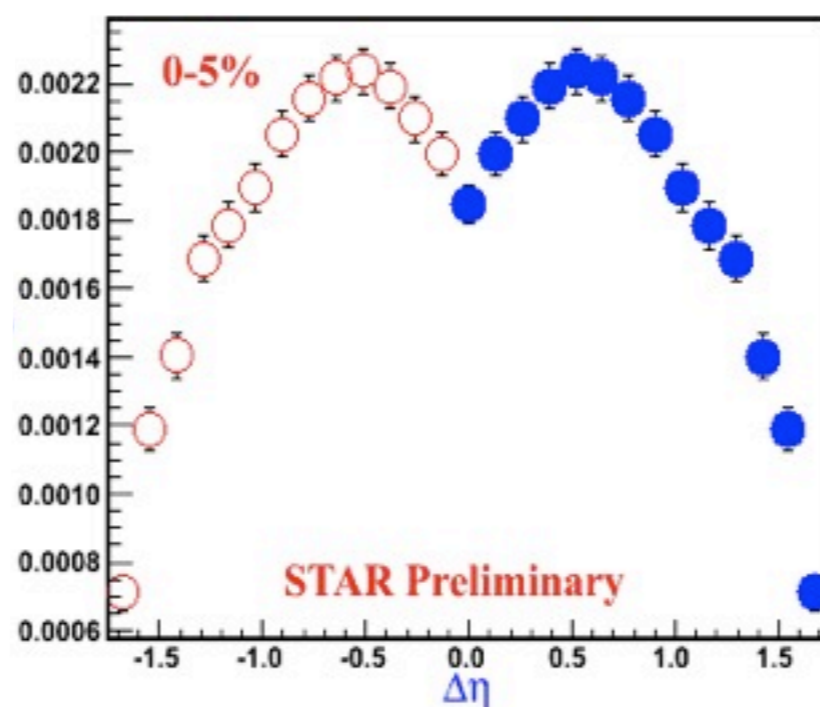


Dip at $\Delta\eta=0$ in part due to track merging, under investigation



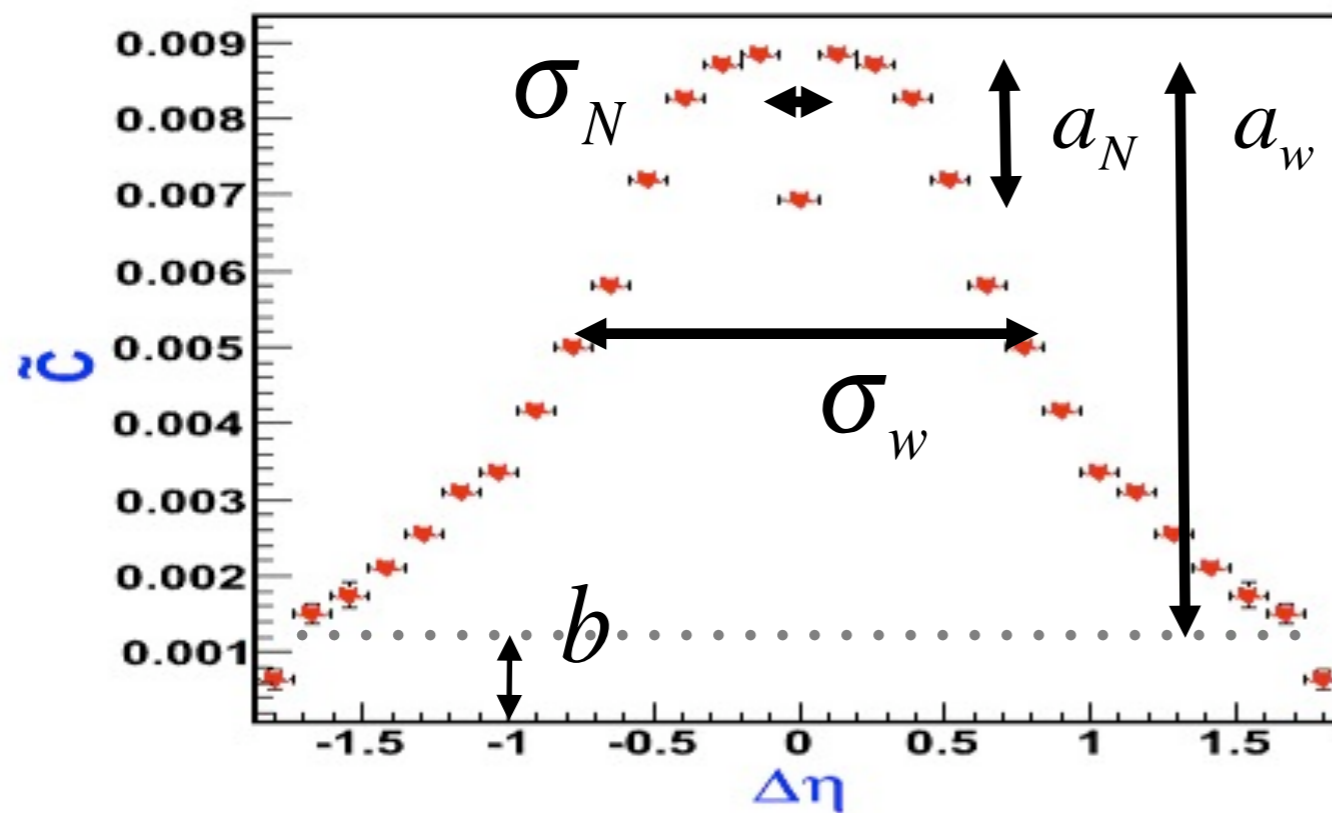


$\Delta\eta$ projection
with $|\Delta\phi| < 1$ rad



Parameterization and Fit

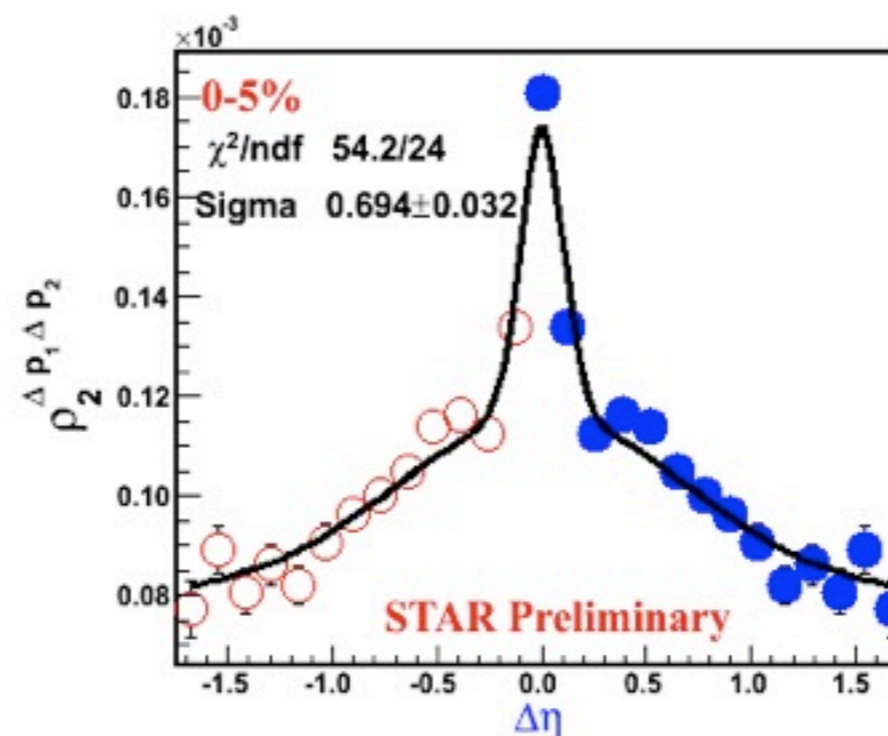
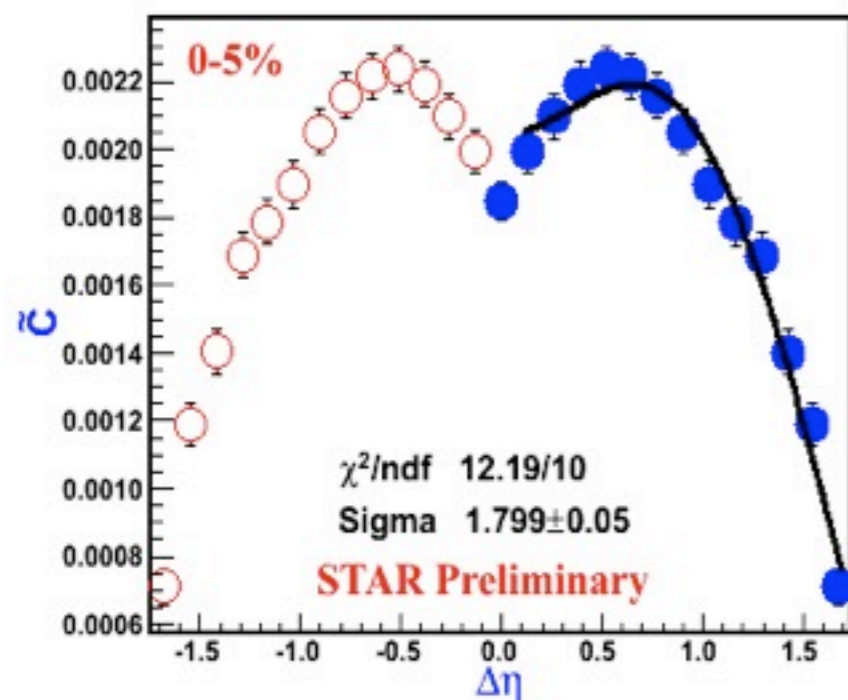
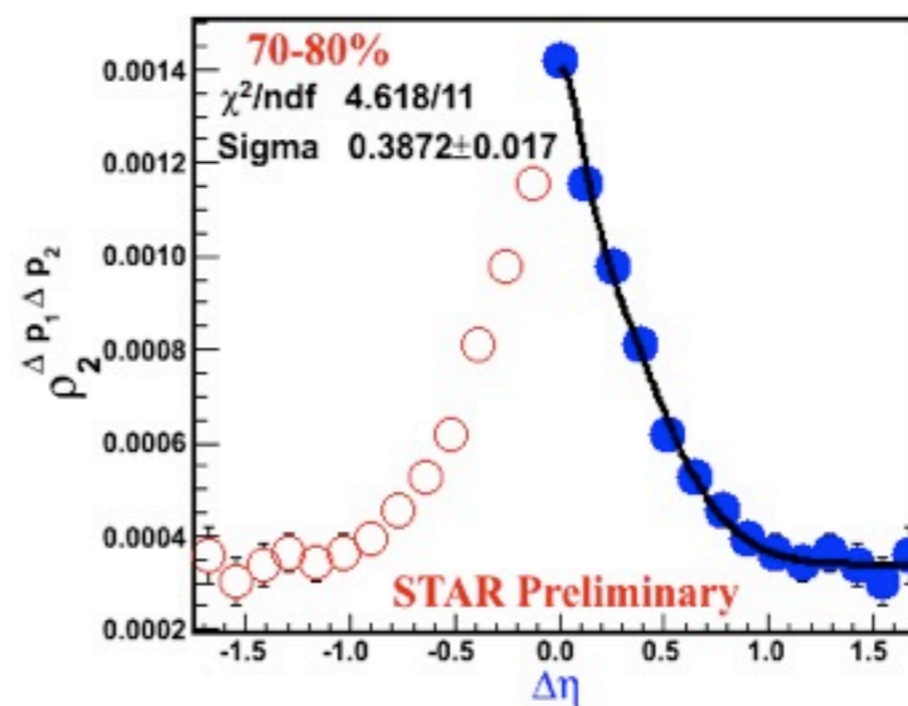
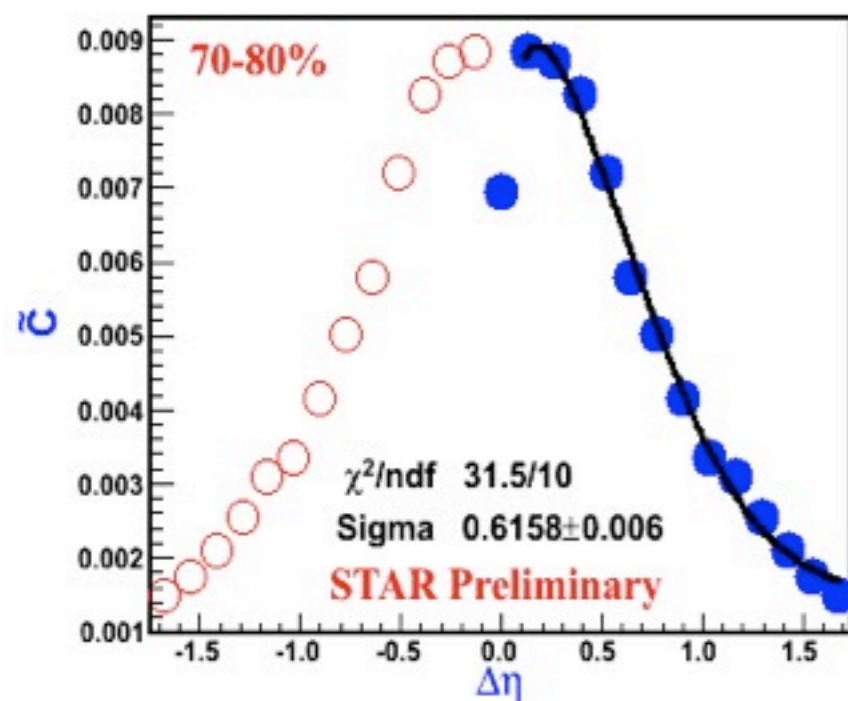
$$\tilde{C}(b, a_w, \sigma_w, a_n, \sigma_n) = b + a_w \exp(-\Delta\eta^2 / 2\sigma_w^2) + a_n \exp(-\Delta\eta^2 / 2\sigma_n^2)$$



σ_w Increase with centrality determines the viscosity

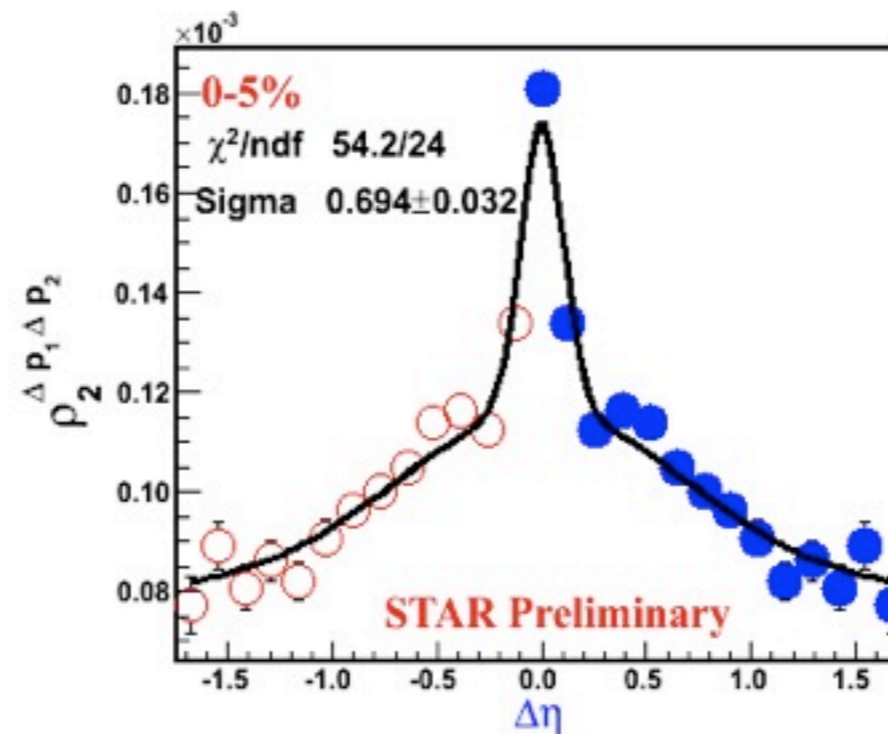
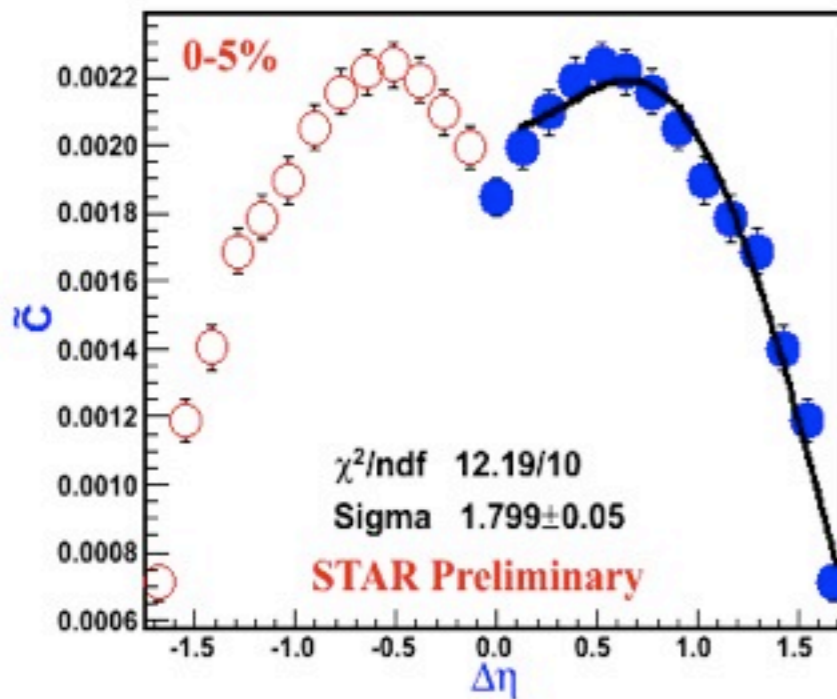
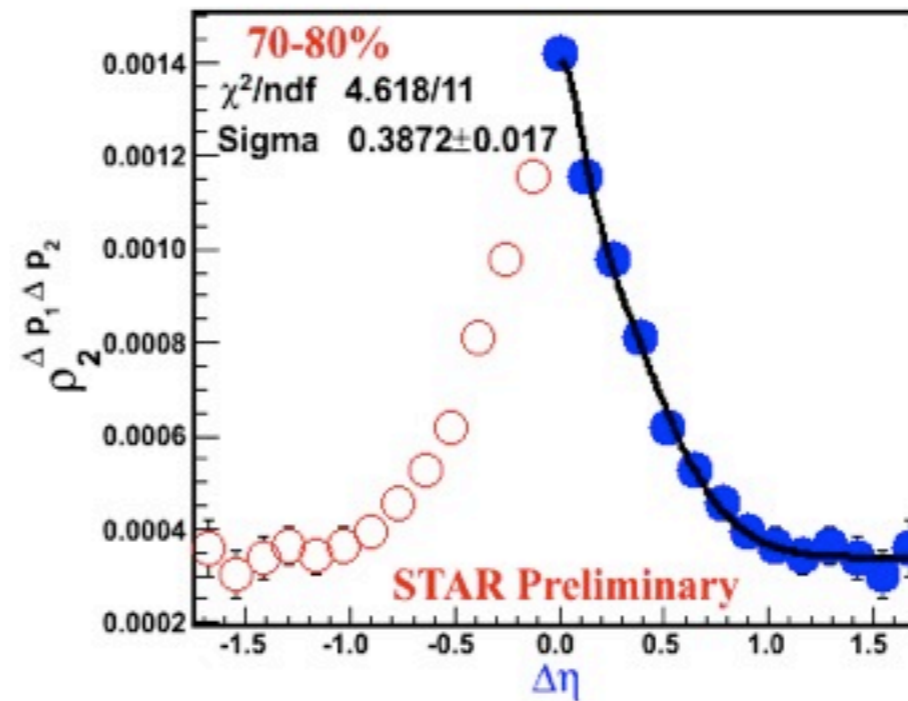
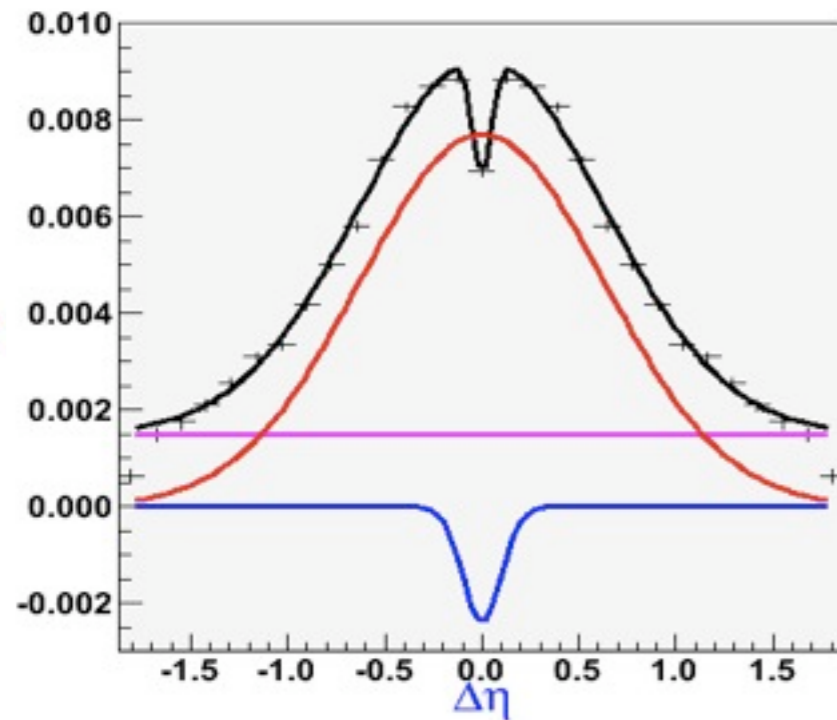
Fit Results

Observations:
Broadening with collision centrality
Change in strength and shape (not just dilution)

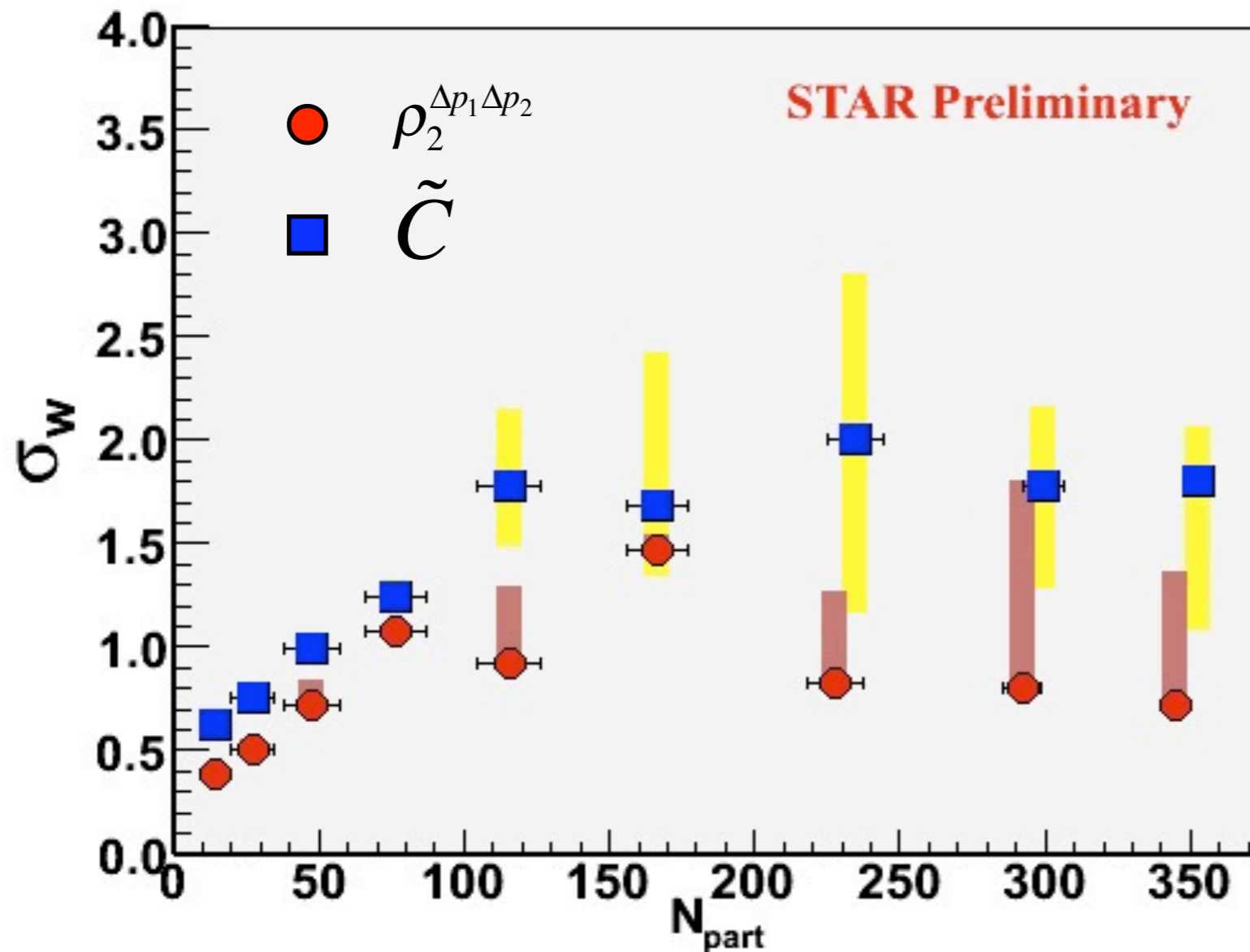


Fit Results

Observations:
Broadening with collision centrality
Change in strength and shape (not just dilution)



Results: Width vs Centrality



 **Statistical errors**

\tilde{C}

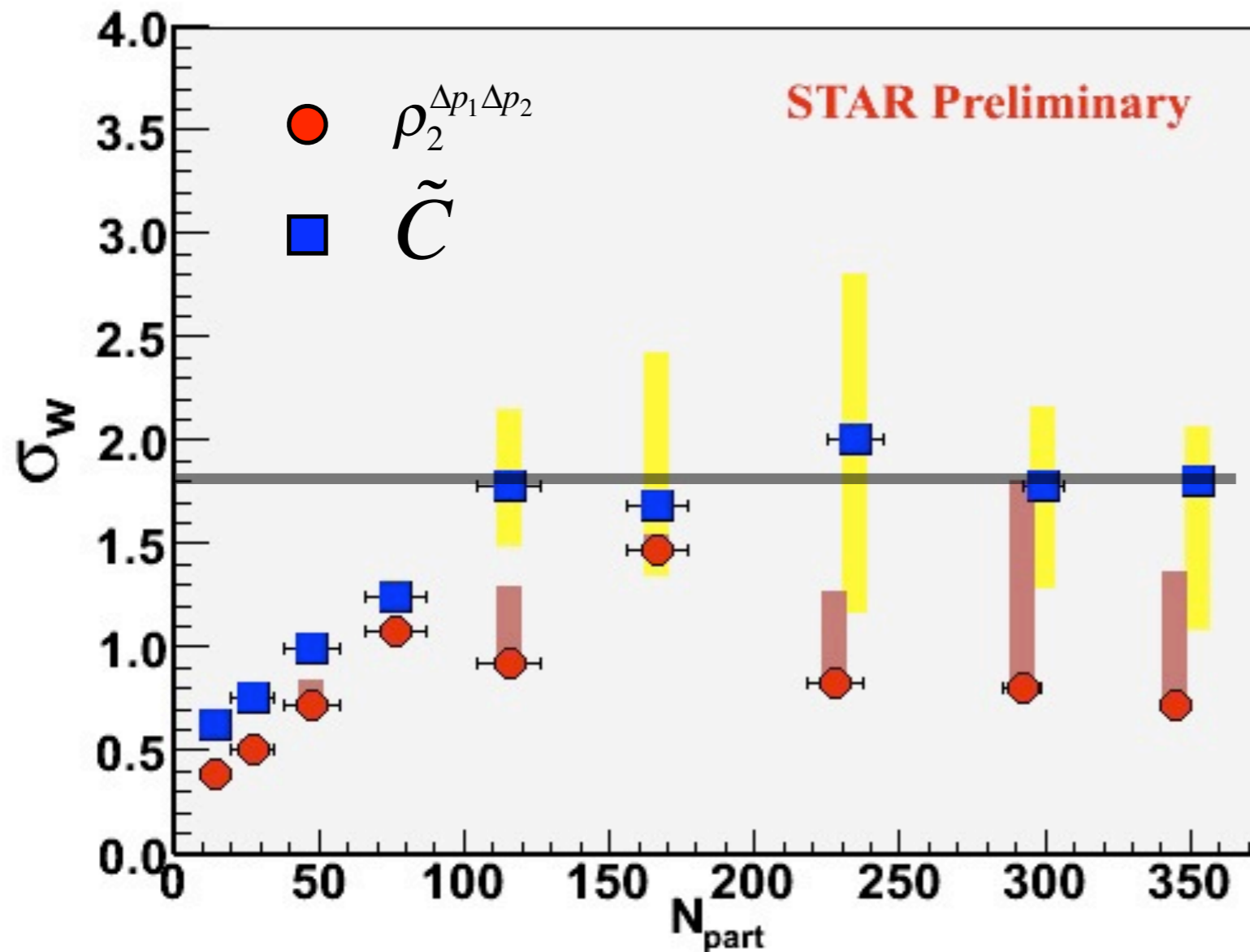
$$\sigma_w \propto N_{part} \quad \text{for } N_{part} < 130$$

$$\sigma_w \approx \text{constant} \quad \text{for } N_{part} > 130$$

$$\sigma_w \approx 1.8$$

$$\sigma_w \approx 0.5 \quad \text{for } N_{part}=2$$

Results: Width vs Centrality



Statistical errors

\tilde{C}

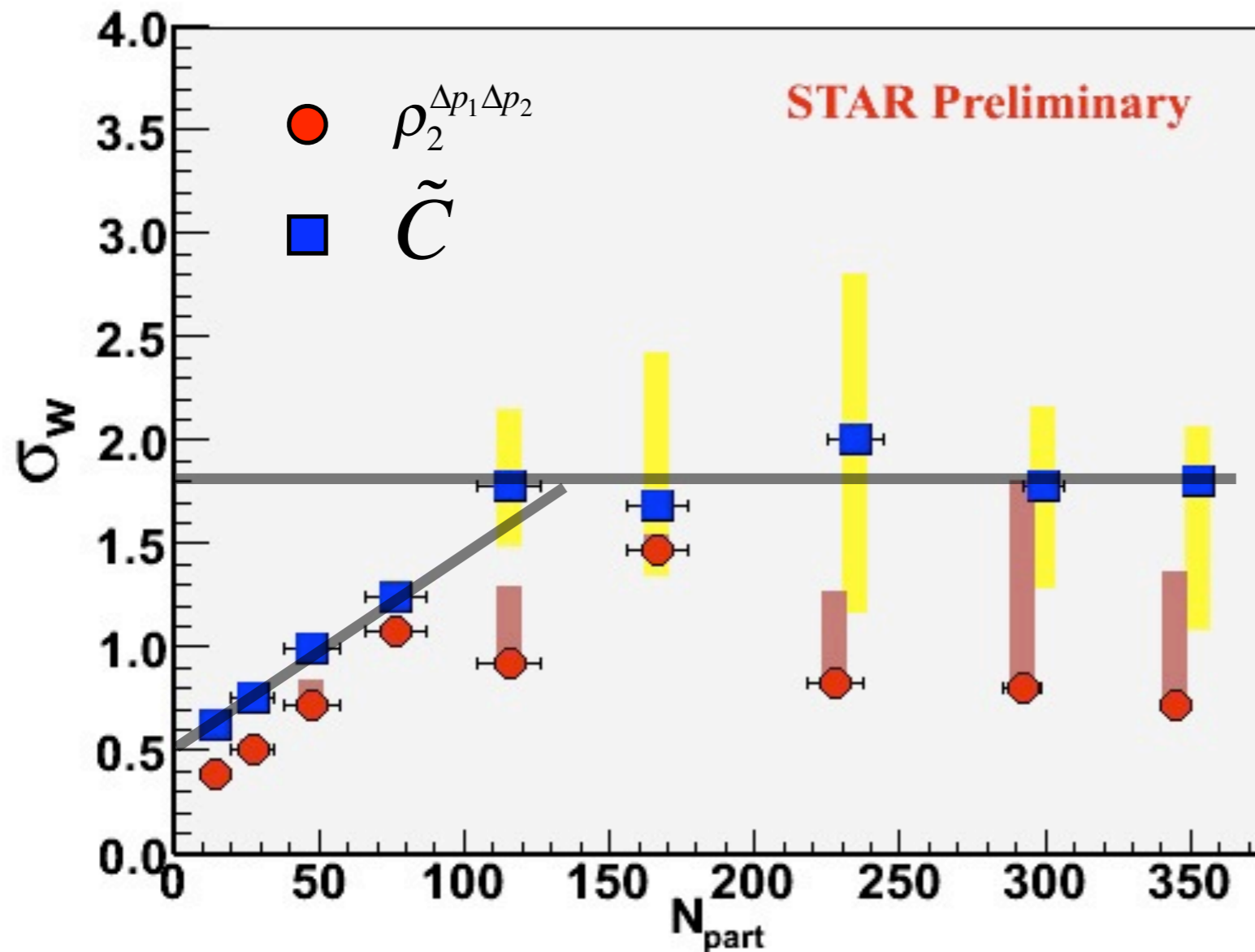
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Results: Width vs Centrality



 **Statistical errors**

\tilde{C}

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$$\sigma_w \approx \text{constant} \quad \text{for } N_{part} > 130$$

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$$\sigma_w \approx 0.5 \quad \text{for } N_{part}=2$$

Estimation of the Kinematic Viscosity (1)

S. Gavin, M. Abdel-Aziz, nucl-th/060606

$$v = \frac{\sigma_c^2 - \sigma_p^2}{4(\tau_{f,p}^{-1} - \tau_{f,c}^{-1})}$$

Central Au+Au: $\tau_{f,c} \sim 20 \text{ fm}$

$$\frac{\tilde{C}}{\sigma_w \approx 1.8} \quad \frac{\rho_2^{\Delta p_1 \Delta p_2}}{\sigma_w \approx 1.}$$

p+p: $\tau_{f,p} \sim 1 \text{ fm} / c$ $\sigma_w \approx 0.5$ $\sigma_w \approx 0.3$

$$\eta / s : 0.64^{+0.16}_{-0.25} \quad 0.08^{+0.15}$$

Caveats:

Model Dependent

Measured value depends on Temperature, Freeze-out Times

$\tau_{f,p} \sim 1 \text{ fm}/c$ is small, should we use a larger value? (greatest sensitivity)

$\tau_{f,c} \sim 20 \text{ fm}/c$ is large, should we use a smaller value?

Same as STAR, J. Phys.
G32, L37, 2006 as p

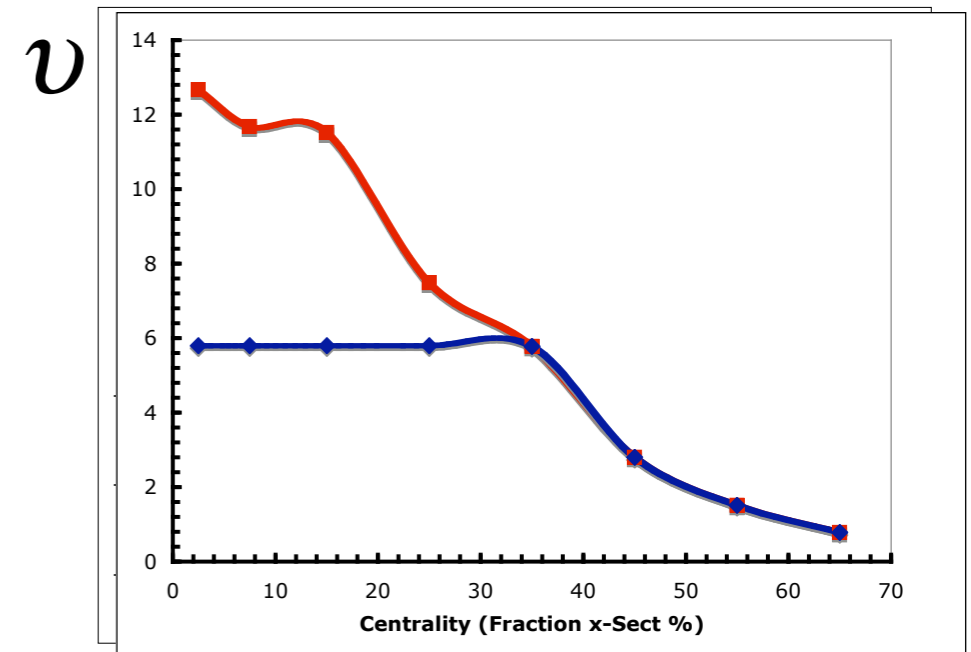
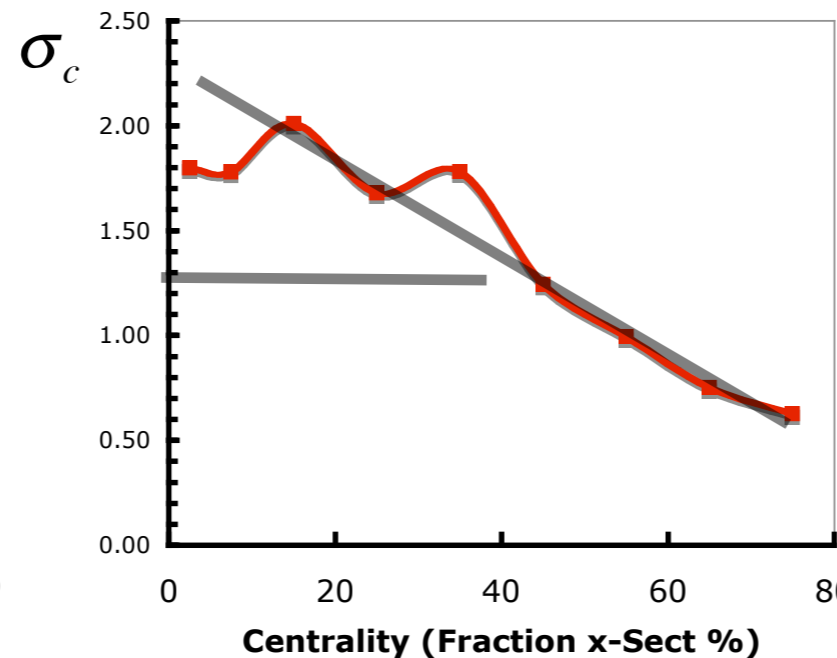
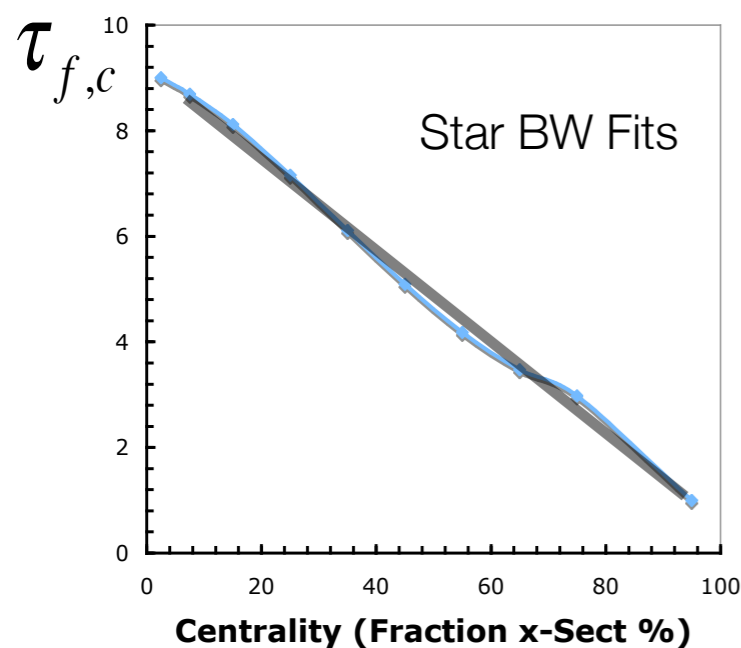
Estimation of the Kinematic Viscosity (2)

- Assume Diffusion Contribution (vs centrality) dominates

$$\sigma_c^2 = \sigma_{\text{Diffusion}}^2 + \sigma_{\text{Thermal}}^2 + \sigma_0^2 \quad \sigma_{\text{Diffusion}}^2 \gg \sigma_{\text{Thermal}}^2 \quad \text{or} \quad \frac{d\sigma_{\text{Diffusion}}^2}{dN_{\text{part}}} \gg \frac{d\sigma_{\text{Thermal}}^2}{dN_{\text{part}}}$$

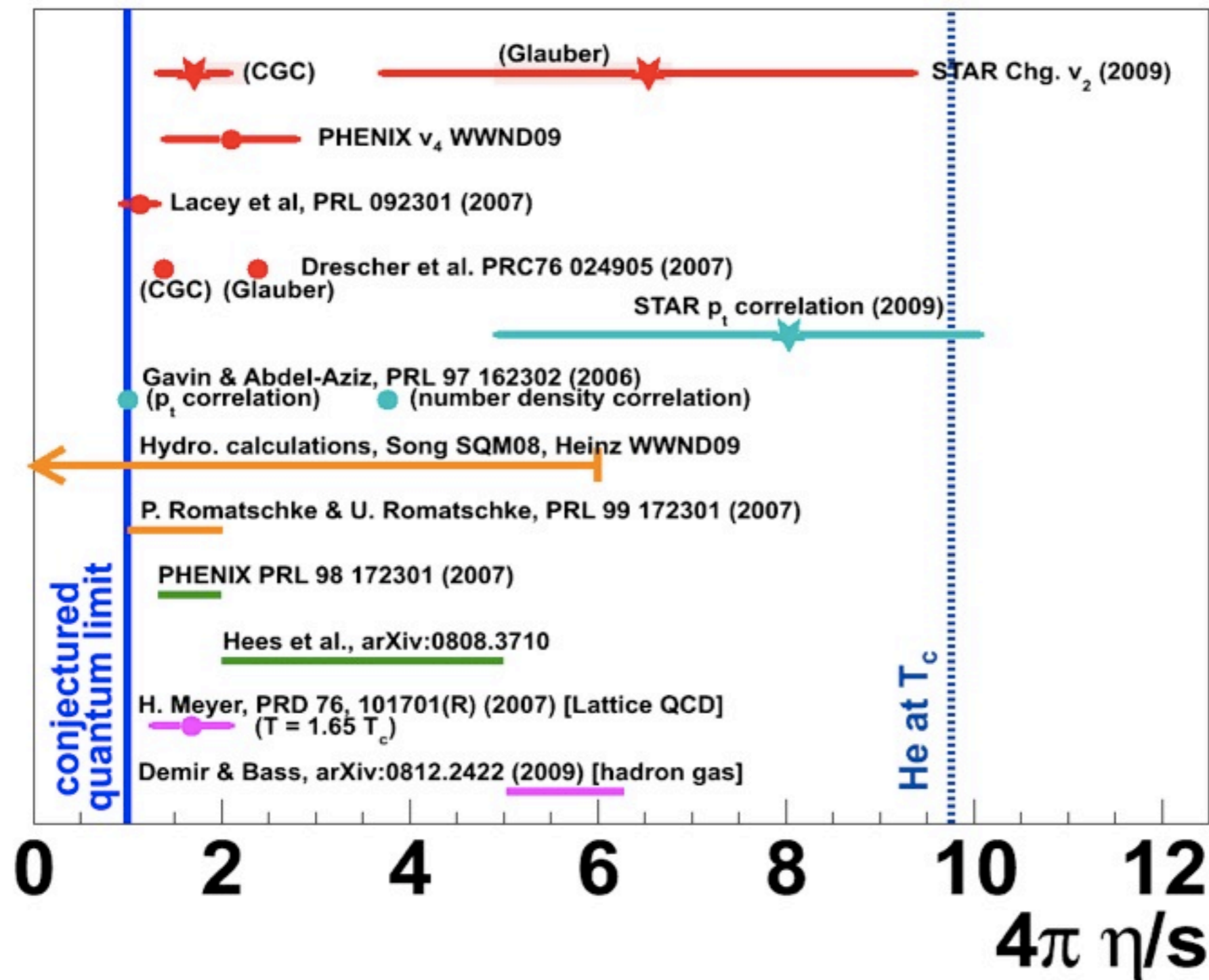
- Derivatives w.r.t. N_{part} eliminates dependence on $\tau_{f,p}$

$$\frac{d(\sigma_c^2 - \sigma_p^2)}{dN_{\text{part}}} = 4v \frac{d(\tau_{f,p}^{-1} - \tau_{f,c}^{-1})}{dN_{\text{part}}} \quad \Rightarrow \quad v = \frac{1}{4} \frac{\frac{d\sigma_c^2}{dN_{\text{part}}}}{\frac{d\tau_{f,c}^{-1}}{dN_{\text{part}}}} \quad \text{or} \quad v = \frac{1}{2} \sigma_c \tau_{f,c}^2 \frac{d\sigma_c/dN_{\text{part}}}{d\tau_{f,c}/dN_{\text{part}}}$$



Viscosity Results Compilation

STAR Results
Preliminary



Summary

- Presented measurement of η / s based on pt differential corr. fct. \tilde{C}
- Width $\sigma_w \propto N_{part}$ for $N_{part} < 130$; $\sigma_w \approx \text{constant} \approx 1.8$ for $N_{part} > 130$
- $\eta / s = 0.64^{+0.16}_{-0.25}$ based on $v = \frac{\sigma_c^2 - \sigma_p^2}{4(\tau_{f,p}^{-1} - \tau_{f,c}^{-1})}$ $\tau_{f,p} \sim 1\text{fm}/c$ $\tau_{f,c} \sim 20\text{fm}/c$
- Based on $v = \frac{1}{2} \sigma_c \tau_{f,c}^2 \frac{d\sigma_c/dN_{part}}{d\tau_{f,c}/dN_{part}}$
 - Observe much larger values and variation with collision centrality.
- Two results are mutually inconsistent, and at variance with v_2 based estimates.
- What are we missing?
- Rechecking measurements of C and widths determination
- Are the model assumptions valid?
 - Causality, Viscosity dominance on broadening, temperature dependence on centrality, hadronic vs QGP viscosity, radial flow, etc.